PERFORMANCE CAPABILITY OF A DAMAGED LIGHTER-THAN-AIR VEHILCE OPERATING IN THE NEAR SPACE REGIME

THESIS

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Abstract

This study investigates the ability of a high-altitude airship to maintain lift following the compromise of its lifting gas envelope. Accepted engineering principles are applied to develop a model that provides comparative analyses for airship depressurization alternatives following hull compromise. Specifically, maintaining lifting gas envelope overpressure to provide controllability in wind currents while sacrificing some buoyancy is compared with allowing envelope depressurization to occur with the goal of maintaining greater buoyancy as long as possible. The model provides insights to alternatives for recovering a damaged vehicle and its payload. In particular, the analysis demonstrates that maintaining the ability to navigate while forfeiting buoyancy can provide additional down-range maneuver capability. In some cases preserving the airship's hull overpressure for some period of time following compromise, vice allowing a slow depressurization to atmospheric equilibrium, extends the distance a damaged airship can sustain controlled navigation as much as eighty percent. However, the airship will forfeit nearly twenty percent of the altitude it would otherwise preserve by not forcing a constant hull overpressure.

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To my dad

Acknowledgments

I would like to thank my God for the opportunity to accomplish this academic program as well as for the many blessings He placed in my life. I'm particularly thankful to and for my awesome wife and terrific kids who each seeks to encourage me everyday. Their confidence gives me the courage to keep trying. Thanks also to my mom and dad who instilled in me the values of hard work and life-long learning.

Thanks to my committee members for their commitment to guiding me through this research project. I took their inputs as challenges and through each challenge I increased in knowledge and confidence.

It has been said, "Everyman can be bigger than he is." I add to that: "…but not without support from others." So many people have challenged and encouraged me through this academic experience and have helped me grow and for that I say, "Thanks."

Charles W. Vogt, Jr.

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B	constant
C	constant
C_D	drag coefficient
D	constant
F_B	buoyant force
F_D	drag force
g	gravity
H	atmospheric height
H	atmospheric pressure scale height
H^*	atmospheric density scale height
h	altitude
L_n	buoyant lift
m	mass
m_{gas}	lifting gas mass
m_{He}	helium mass
m_{pl}	payload mass
m_{st}	airship structural mass
m_{Total}	sum of payload and structural mass
p	pressure
p_{atm}	atmospheric pressure
p_{env}	airship envelope (or hull) pressure
p_o	atmospheric pressure at sea level
R	universal gas constant
T	temperature
T_{avg}	average atmospheric temperature
t	time
u	airship descent speed
v	speed of lifting gas leaking from hull
v_{max}	airship maximum cross range speed
w	elemental atomic weight
w_{air}	atomic weight air
w_{gas}	atomic weight lifting gas
w_{He}	atomic weight helium
z	atmospheric height
Δp	airship hull overpressure
ρ	density
ρ_{air}	atmospheric density
ρ_{airo}	atmospheric density sea level
ρ_{gas}	density lifting gas
ρ_{He}	density helium
ρ_{Heo}	density helium sea level
σp	density ratio

PERFORMANCE CAPABILITY OF A DAMAGED LIGHTER-THAN-AIR VEHICLE

OPERATING IN THE NEAR SPACE REGIME

1. Introduction

1.1 Motivation

Seamless war-fighting integration of United States military space systems is more critical today than any time prior. Theater commanders demand space asset support for critical remote sensing, communication, and precision navigation and timing to enhance their combat operations. But the commander's pull for support places severe technological and financial burdens on the US Air Force to provide that need. The Air Force Space Command Strategic Master Plan for FY 06 and beyond projects initial spending levels at nearly $14 billion to support currently desired military programs. This spend level grows over the next 25 years to nearly $23 billion. That level of spending is exhausting to the Air Force budget and demands that advancing technology keep pace in order to prevent cost growth. In the interim, the theater commander still waits for support.

Space Command is searching for a near term, low cost and low barrier solution to better providing support to the theater. Recently, the concept of lighter-than-air vehicles operating at suborbital altitudes in a region termed "near space" has sparked the imagination of space force providers. Near space represents a region of the earth's atmosphere mostly ignored by military planners. It is the region from approximately 65,000 feet to 300,000 feet. In this region the air density is too small to allow easy exploitation by air-breathing winged aircraft. Simultaneously, the air density is too great to allow sustained orbital operations because of aerodynamic drag effects. Space Command has organized and taken the Air Force lead for developing lighter than air operational concepts in near space to support theater demands for communication and intelligence, surveillance and reconnaissance (ISR). The goal of this research paper is to contribute to the technical body of knowledge regarding vehicle operations in this atmospheric regime.

Advocates endorse the use of lighter-than-air vehicles to carry payloads with sensor suites more typically carried by either unmanned aerial vehicles (UAV) or orbital spacecraft. Numerous projects are currently underway to study concepts of using lighter-than-air vehicles in a theater to meet the ISR and communication needs of the commander. Because the system would be used in a military context, the question of survivability in a hostile environment has surfaced. One question frequently asked is, what impact will rupturing the vehicle's lifting gas envelope have on the system? The question is typically answered with references to a slow diffusion process that implies little concern in understanding the vehicle's ability to remain aloft. As well, anecdotal references are given regarding how difficult it is to destroy a weather balloon. The motivation of this research is to examine the survivability question and provide physical insights to the question about lighter-than-air vehicle survivability when its lifting gas envelope has been ruptured. In the end, this research provides a first-order methodology for understanding lighter-than-air vehicle survivability when an airship's gas envelope has been compromised. Insights will be gained about an airship's descent rates and range capabilities through comparative analysis of possible post-damage survivability course of action options.

1.2 Background

Traditionally, the warfighter has come to expect a segment of their space support to be provided from an orbiting spacecraft located in some type of orbit about the earth. These satellites have provided electro-optical and infrared imaging from low earth orbits, timing and navigation from medium earth orbits, and communication from geostationary orbit. While these examples are hardly exhaustive of military missions and orbits, they represent the traditional way military planners have looked at space operations.

The Department of Defense (DoD) often finds itself in competition with other national agencies for support from space-based systems. A theater commander may desire imagery support from a national overhead electro-optical system to target a critical adversary asset. However, he doesn't own the imaging spacecraft and has to petition a national agency to provide service and then wait in line behind other national security priorities for photos.

Joint Warfighting Space (JWS) is a DoD program with the goal of providing the theater commander flexibility and agility in space support. JWS in its fullest sense is an operating concept. It's a rapid reaction networked space constellation, dedicated to the joint force commander and integrated with National Security Space systems. [5] The space system is projected to be a tactical system designed to operationalize space for the benefit of the warfighter. It will provide rapid access to space, placing systems on orbit in days and weeks instead of months. The systems will be small spacecraft that are designed to operate for months and be interoperable with current and future theater assets.

The first funded step of JWS is two demonstrator satellites—TACSAT I and II (recently designated JWS SAT). TACSAT I, being built by the Naval Research Laboratory, is a cylindrical vehicle about 20 inches high and 40 inches in diameter. It will be outfitted with visible-light and infrared cameras and have its own Secret Internet Protocol Router Network (SIPRNET) address from which users can access data stored onboard the spacecraft. [14] The mission is designed to validate a concept of operations for a tactical imager spacecraft providing support to a theater commander. The demonstration vehicle is scheduled for launch no earlier than January 2006 on board a Falcon I booster.

The Falcon booster will make its debut flight as the first launch system developed to support JWS. In 2004, the Air Force and the Defense Advanced Research Programs Agency (DARPA) under the Operational Responsive Space (ORS) initiative, contracted with SpaceX Corporation to build a low-cost, rapidly-readied booster to support TACSAT. The system will cost less than $6 million per launch and be processed for launch in only days.

TACSAT I had set a budget goal of placing the system on orbit for $15 million; including launch costs. An additional $15 million is set aside for TACSAT II. However, two follow-on demonstrations are waiting to be funded. Obvious is that the cost of on-orbit operations, even with significant reductions in launch costs, requires large capital investments. The funding required and technology development process makes it evident that an on-orbit JWS segment is not feasible in the near years. However, the theater commander's need for support continues today.

To mitigate the lag in deploying JWS support, Space Command has looked for alternate operational concepts to bring space support to commanders. The Space Battlelab and command officials briefed the Air Force Chief of Staff in December 2004, on an alternative—high altitude, lighter-than-air vehicles. Following that meeting Space Command was directed to be the Air Force's lead on developing operational concepts for near space. The command's strategy is to develop both a traditional on-orbit and non-traditional near space approach to support JWS. The command is aggressively moving forward to develop lighter-than-air systems to support the non-orbital approach.

In early 2005, a research paper released by the battlelab detailed basic operational concepts for lighter-than-air technology. [16:13] It detailed the combat effects possible from near space as well as vehicle concepts that could support the capabilities. Its discussions included insights on survivability of lighter-than-air vehicles. The battlelab paper refers to a slow diffusion process that would cause a vehicle to fail if the lifting gas envelope is punctured. The paper adds anecdotal support by referencing a story of a renegade research balloon that required over 1,000 rounds from Canadian F-18s and six days time to bring down.

However, little attention has been given to a physical explanation of what occurs when a lighter-than-air vehicle's lifting gas envelope is punctured. In fact, the response has been to refer to the research balloon story to illustrate the robust nature of lighter-than-air systems. The generic, across-the-board application of this anecdotal evidence can place into question the true survivability of an airship. Factors such as vehicle rigidity and control surface integrity can be compromised moving the system to failure more quickly depending on the system design. A vehicle that requires some overpressure to maintain its ability to be controlled may fail quickly when damaged. These insights may be extremely important to systems operators and planners who desire to recover the vehicle and its payload or maximize its remaining useful life over a specific location of interest.

1.3 Research Objectives

The aim of this research work is to begin examination of the diffusion process that will cause a lighter-than-air vehicle to fail when its gas envelope is damaged. The reason behind the work is to provide the community developing these systems with some critical thinking regarding this failure mode. While it is clear that the loss of lifting gas will affect buoyancy and result in decreased performance capability, the true impacts remain somewhat clouded by speculation and generalization. Possibly, a general understanding is all that is required for analysis and by examining this question it might be shown that anecdotal evidence does in fact sufficiently address the question of survivability.

Specifically, this project accomplishes three main objectives. First, it develops a mathematical expression to model lift capacity of a lighter-than-air vehicle with a damaged lifting gas envelope. Next, it attempts to characterize airship performance following hull damage—that is the ability to hold a course or maintain station. Finally, it examines possible time to failure criteria for a lighter-than-air vehicle operating under specified atmospheric conditions.

The vehicle concepts being considered for this mission are diverse. They range from a free-floating balloon to a rigid airship structure. For this reason the objectives will be examined with some respect given to vehicle type and capabilities. Because the free-floating system in the anecdote might behave differently than a propelled system, it is important to compare a navigable airship's performance with the free-floating system used as an illustration of survivability. It is hypothesized that since an airship relies on vehicle hull pressure to maintain its navigation capability, keeping the hull pressure higher following rupture will enable it to travel further down range. Conversely, allowing it to simply depressurize to atmospheric equilibrium will preserve altitude. The take away is initial insights into how survivability can or should be addressed by different lighter-than-air system operators and designers. The objectives should also provide a baseline to start future discussions regarding survivability.

1.4 Thesis Overview

This paper uses well-accepted engineering first principles to explain what occurs when a vehicle's lifting gas envelope is compromised. The intention is to provide a broad examination of performance expectations and will take advantage of well understood engineering assumptions to provide insights. The reader should be aware that in order to effectively model the process, simplifications must be made to provide the broad overview intended by this paper.

This analysis begins with understanding what makes a lighter-than-air system generate lift ability. The physical mechanisms that control the sudden loss of lifting gas by a lighter-than-air system are examined. An attempt is made to model how a compromised vehicle would behave following damage. Governing equations are investigated to help illustrate performance capability and predict future performance. Well understood principles such as Newton's Laws of Motion, Archimedes' Principle, Bernoulli's Equation and the ideal gas law are leveraged to help explain performance.

Application is made across a small spectrum of vehicle types. Specifically, semi-rigid airships assumed to have a propulsion capability are examined for insights. An overview of lighter-than-air vehicle types is made in chapter two. The results from the application of the engineering modeling are captured to provide feedback on the impacts of losing lift.

This thesis is specifically designed to examine the question of what occurs after a system sustains damage. Aspects of a system's ability to evade attack, mitigate detection or avoid damage are not contained in this work. As well, this work will assume that the bounds of damage are not so severe that complete system integrity is lost. In other words, the system retains some ability to hold lifting gas and generate lift.

2. Literature Review

2.1 Chapter Overview

Lighter-than-air flight has been used for more than 230 years for numerous applications from sport to science. The phenomenon is hardly a new concept. Today, a warfighting application is emerging for high-altitude communication and surveillance platforms. Lighter-than-air platforms are being tested to support those applications. Lighter-than-air systems are based on well-understood engineering principles. The purpose of this chapter is to examine these principles and how they apply to lighter-than-air flight.

The chapter provides a physical understanding of principles used to develop a performance model of an airship. This sets the stage for examining performance of a combat damaged airship. The section begins with a discussion of the operating environment—Earth's atmosphere—particularly the upper troposphere and lower stratosphere. Next, an examination of buoyant force and its associated lift capability will be made. Combining Newton's laws of motion and Archimedes' Principle regarding forces on a body immersed in a fluid, an expression is developed to describe lift capability of a lighter-than-air system.

2.2 Background

After a nearly 4,000 mile trip, a Canadian research balloon carrying an atmospheric research payload came to rest in a field in Finland. The 100 meter tall balloon had failed to terminate its three-day mission and drifted for 10 days over the Atlantic in August 1998. During that trip the rogue balloon threatened trans-Atlantic flight routes and caused numerous flights to be redirected to prevent a collision with the erratic flight. The balloon, which can reach altitudes as high as 130,000 feet, caused enough concern to generate military responses from the United States, Canada, and Great Britain. Early in the episode the Canadian Air Force scrambled F-18 fighters to try to destroy the vehicle. Despite over 1,000 twenty millimeter cannon shots at the balloon, the fighters were unable to bring the vehicle down. [17:14] The exact altitude of this engagement was not verified. However, the damaged balloon continued to cross the Atlantic Ocean at altitudes between 27,000 and 37,000 feet. Many observers thought this errant flight might be the first lighter-than-air vehicle to make a round-the-world circuit. But not to be, on 3 September 1998, the balloon's flight ended.

Figure 2.1—Rogue Canadian research balloon shortly before landing in Finland after a 10-day flight. Children climb on the remains of the balloon after it returned to Earth's surface. [1]

This flight has become a lynch pin of anecdotal evidence of airship survivability. It is abundantly clear that simply puncturing the lifting envelope of the research balloon couldn't cause catastrophic failure. Although it's not clear how the vehicle was struck by the F-18's cannon, it is safe to assume that at least some projectiles fired at the balloon were able to puncture its skin. Yet the vehicle's flight continued for some time before crashing to the earth. Using this anecdote as motivation, an exploration of physical principles involved in airship flight is warranted.

2.3 Airship and Lighter-than-Air Technology

Lighter-than-air flight is achieved by exploiting the propensity of a lighter fluid to rise to a point of equilibrium in a heavier fluid. Designing a vehicle to achieve this lift has a wide range of variation. Vehicles can be as simple as a helium-filled balloon or as complex as a framed and propelled lifting body containing a lifting gas. The most common lighter-than-air vehicles are weather balloons. Often weather balloons are in actuality not balloons as their skins are not "stretched" by the internal gas pressure. Instead, they are better described as envelopes that contain a lifting gas, which expands as the envelope rises. However, the envelope material will not stretch and will fail unless internal pressure is relieved as the gas expands. An airship, sometimes called a "dirigible," can be considered a special case of balloon, which has been designed with a specific geometry that presents a lower aerodynamic resistance to motion. Usually, an airship has a propulsion system on board to allow it autonomy of motion rather than being subject to motion along the course of prevailing winds. Over time three main classes of airships (Figure 2-2) have been developed: non-rigid; semi-rigid; and rigid. [8:24]

The non-rigid airship is a pressurized gas envelope containing a lifting gas. Any type of payload can be contained in a carriage attached to the envelope. The envelope relies mainly on a small overpressure to maintain its shape and often vents lifting gas through some pressure relief system to prevent overexpansion as it rises. When gas expansion has completely filled the containing envelope, the vehicle has reached its "pressure altitude"—the highest altitude it can achieve without increasing internal overpressure. Because these vehicles retain their geometry only by gas pressure, they are capable of only slow horizontal speeds—typically 20 to 40 knots. Higher speeds present the threat of deformation of the leading envelope surface due to high stagnation pressure. Also, non-rigid systems offer little resistance to bending and shear forces due to loading and environmental forces.

The second airship type is a semi-rigid vehicle. The semi-rigid airship is similar to the non-rigid, but adds a reinforcing keel along the base of the envelope and leading surface stiffener to the envelope. The keel adds strength to the envelope and allows payload capacities to be increased. The stiffener strengthens the forward edge and helps

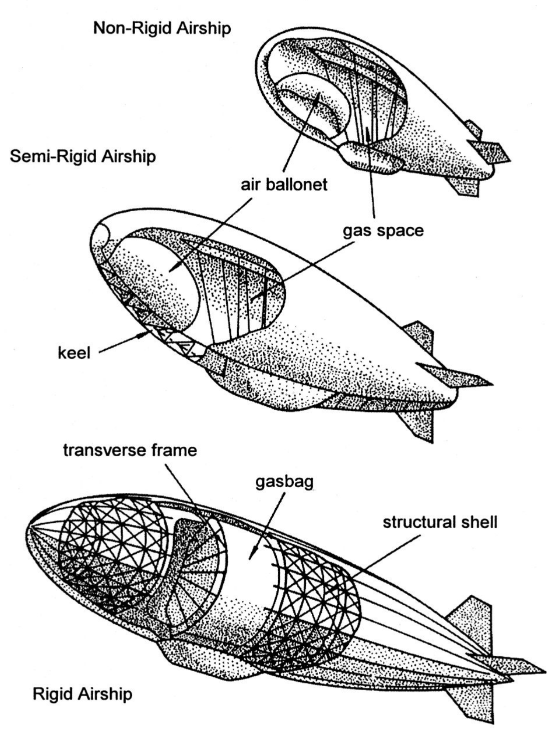


Figure 2.2—Types of Lighter-than-Air Airships

prevent deformation of the envelope due to pressure during forward motion.

The final airship type is the rigid vehicle. This type of vehicle contains a rigid structure or frame with a gas envelope or "bag" inside the frame. This frame provides several advantages. First, it resists shear and bending forces placed on the envelope by a payload and environmental forces. Next, it ensures the integrity of the envelope geometry under forces caused by increased forward velocity and does not require an "overpressure" condition to maintain the shape of the vehicle. Finally, it helps the vehicle maintain its geometry during descent.

Lighter-than-air vehicle geometry is often a function of system propulsion requirements. Some systems require no method of propulsion. These systems are known as free floating and will follow the prevailing wind currents as they soar. Aerodynamically efficient geometry is not typically a concern for this type of vehicle and most often they are spherical. As the need for navigation and control of a vehicle increases, propulsion systems can be added. These systems are typically motorized propellers that move a vehicle. These systems are powerful enough to prevent the vehicle from being adversely affected by wind currents and allow steering to be accomplished. Geometry is more important for this type of vehicle. Typically airships designs are tuned to an optimum fineness ratio to minimize drag forces on a propelled vehicle. The fineness ratio is simply a measure of the slenderness of the body and is a ratio of the vehicle's length to its maximum diameter. [9:57] Research has demonstrated that larger fineness ratios have significant impacts on vehicle drag for operations in high head wind conditions.

Finally, when examining lighter-than-air vehicles it is important to understand the physics of an ideal gas. Both air and typically used lifting gasses are considered to behave like an ideal gas. An ideal gas is defined as a real gas that is not approaching liquefaction. [11:14] Such a gas can be modeled by the ideal gas equation.

$$\rho = \frac{pw}{RT} \tag{2.1}$$

This expression states that the density (ρ) of a gas is proportional to the pressure (p) and its atomic weight (w), and inversely proportional to its temperature (T), and a constant (R). Inside the airship's lifting gas envelope the pressure decreases uniformly with increasing altitude as the pressure surrounding the envelope decreases. Temperature changes inside the hull as it rises are assumed to be negligible in this analysis for reasons that will be discussed later. Since a fixed mass of gas exists inside the airship's hull, any changes in lifting gas density must result from pressure changes. The result is an increase in gas volume as the airship rises. Because very little elasticity is present in typical envelope materials the threat of rupture becomes an important consideration. To reduce the threat, many envelopes are equipped with overpressure valves or escape holes, which allow the optimum overpressure to be maintained as the vehicle rises. If volume can no longer be increased during ascent and gas is expelled to the atmosphere through a relief valve, a portion of the airship's lift capacity will be lost. The result might be the forced descent of the airship. This concept of lifting gas mass and its impact on lift will be examined further later in this chapter in a discussion of airship lift and volume calculations.

The lighter-than-air vehicle is optimized to operate in the confines of Earth's atmosphere. It capitalizes on the sea of air present over the planet's surface to develop buoyant lift. A good understanding of buoyancy and the Earth's atmosphere is appropriate to develop.

2.4 Fundamental Principles

2.4.1 Earth's Atmosphere

The Earth is blanketed with a layer of fluid held in place by gravity. We call this Earth's atmosphere. It is composed a number of elemental gasses commonly referred to as air. Also included in the atmosphere is water vapor. For the purpose of this work, Earth's atmosphere is assumed to be a dry mix of air's three major components: nitrogen (N_2), oxygen (O_2), and Argon (Ar). Each of these elements possesses mass and compose some portion of the air mixture. [2:72]

Table 2.1—Composition of Earth's Atmosphere

Basic composition of dry air in Earth's atmosphere

Component	**Fraction**	**Molecular Wt**
Nitrogen (N_2)	0.7809	28.01
Oxygen (O_2)	0.2095	32
Argon (A)	0.00934	39.95
Air	0.99974	28.95

Dalton's Law helps to explain the pressure exerted on Earth's surface and other portions of the atmosphere. Understanding that the individual constituents of air possess mass, then the total pressure exerted on a surface by air is simply the sum of the pressures from individual components contained in a given volume multiplied by their percentage composition of the total volume. If the Earth's atmosphere is taken as the control volume, then a column of atmospheric height z exerts a pressure proportional to the sum of the weight of its components. Assume height z_2 is an atmospheric altitude above z_1. The mass of air molecules at z_1 are additive with the mass of air molecules at z_2 exerting a total force at the base of the column. It is understood that the earth's atmospheric density decreases with altitude. Equation 2.2 shows that atmospheric pressure will decrease with increasing altitude. This idea can also be shown Figure 2.3. The figure shows how the pressure on a column of air decreases as the column height increases. The term dp is negative as pressure decreases as altitude increases because air density is decreasing.

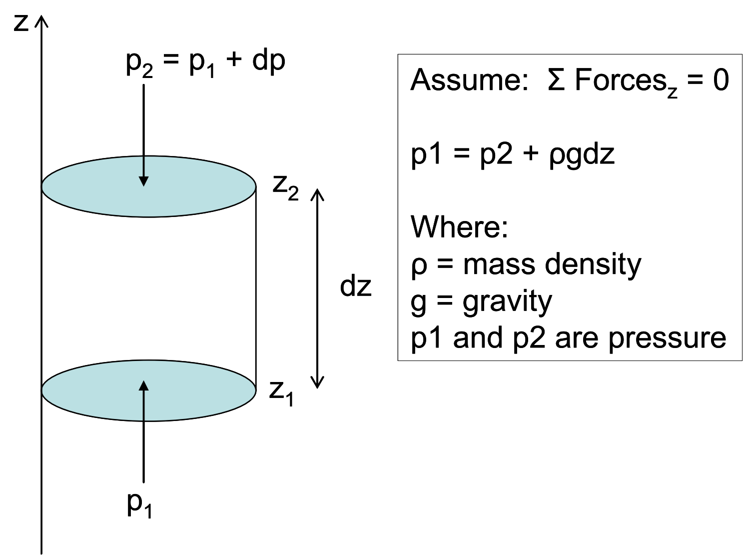


Figure 2.3—Atmospheric pressure change along a column of air

The previous description can be illustrated mathematically by looking at the density of a gas mixture. The force exerted by a column of air is the pressure exerted by the atmosphere multiplied over the area the pressure is exerted upon.

$$p = \int_{H1}^{H2} \rho g dz \qquad (2.2)$$

Separating and solving the differential equation, pressure can be represented as a hydrostatic approximation.

$$\frac{dp}{dz} = -\rho g \qquad (2.3)$$

This approximation assumes Earth's atmosphere is a well-behaved uniform fluid. This assumption is far from the truth. In fact Earth's atmosphere is far from uniform when examining a particular region. This fact quickly becomes evident to the pilot of an airplane flying on a hot summer afternoon. Ground heating of air causes mixing with cooler air masses above and results in rising air masses. The occupants of the plane experience this mixing in the form of a bumpy ride due to turbulence. In fact it is a mass of warm, less dense air moving through a mass of cooler air. Taken to another level, masses of rising and falling air, particularly of differing moisture contents contribute to create weather and produce the rain. Using the hydrostatic approach to predict the pressure exerted by a column of air assumes the Earth is a perfectly spherical mass with a gravitational acceleration vector pointing normal to the Earth's surface. At the intersection point Earth's surface is assumed to be flat.

The hydrostatic approximation provides sufficient understanding of the atmosphere's behavior to allow first-order modeling of the air mass surrounding Earth. The relationship provides a generalized characterization of the entire atmosphere as an aggregate and ignores regional inconsistencies. This can be better understood by looking at the composition of the atmosphere.

2.4.1.1 Composition of Earth's Atmosphere

Earth's atmosphere is a series of regions of gas that can be specifically characterized by their behavior—in specific their temperature. [21:24] The region nearest Earth's surface is the troposphere and extends 15 kilometers upward (approximately 50,000 feet). This is the region where humans as well as most life exist. It is characterized by a decreasing temperature gradient starting at an approximate 14° C (57° F) and declining linearly to -60° C (-76° F). About 85 percent of the atmosphere's mass is contained in the troposphere and it is a region of intense mixing.

The upper boundary of the troposphere—the tropopause—marks an altitude at which the temperature change profile reverses itself. The region above the troposphere is known as the stratosphere. It extends vertically to nearly 50 kilometers (approximately 164,000 feet). The temperature rises linearly with altitude in the stratosphere to an average of -2° C (28° F). There is little convective mixing in the stratosphere and it is relatively stable. Despite its stability it is important to understand that in the stratosphere atmospheric mixing via small scale turbulence continues to dominate diffusion, which occurs at greater altitudes when the mean free path between species becomes great enough to allow gas stratification. Therefore the mixing ratio of atmospheric gasses can be assumed constant. Nitrogen, stable oxygen, and ozone exist in sufficient density in the stratosphere to facilitate atmospheric mixing. In fact, this mixing process dominates the atmosphere to nearly 100 kilometers (328,000 feet) and the mean molecular weight of air remains essentially constant. [2:77]

Above the stratosphere are the mesosphere and thermosphere. These regions rise beyond 100 kilometers (over 300,000 feet) and experience both a decreasing and then again increasing temperature lapse rate through the thermosphere. These regions are beyond the scope of this project and for the purpose of the project need not be described further.

2.4.1.2 Properties of Earth's Atmosphere

It is well understood that both atmospheric pressure and density decrease with increasing altitude. As shown in Figure 2.4, both pressure and density decrease exponentially with height. The exponential pressure and density models have

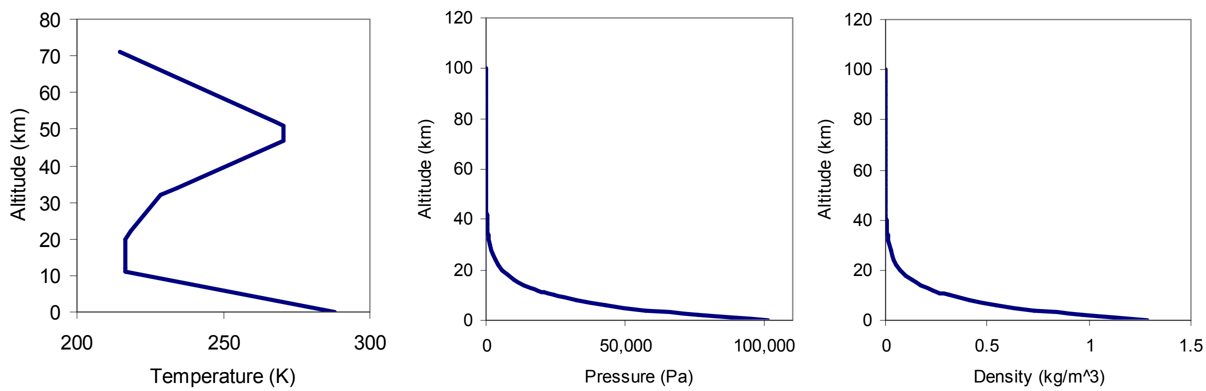


Figure 2.4—Atmospheric temperature, pressure and density gradients

demonstrated a high degree of accuracy in predicting values well in excess of 30 kilometers. [2:56] The basis for this atmospheric model is developing an exponential height constant to relate the rate of change of pressure or density with altitude and then solve for a value based on its proportion of the standard value. Values for atmospheric pressure and density can be predicted by the following equations:

$$p = p_0 \exp(-\frac{h}{H}) \qquad (2.4)$$

$$\rho = \rho_0 \exp(-\frac{h}{H*}) \qquad (2.5)$$

H* represents the scale height constant for modeling density and is related to H by adding the inverse of the temperature lapse rate to the inverse of H. However, since an isothermal atmosphere is being assumed the lapse rate is zero and H can be used as the scale height constant to model density.

Temperature lapse rates in Figure 2.4 reflect predictions modeled by a standard atmosphere model. These are included here to provide perspective on atmospheric temperature. To make use of the scale height model for pressure and density an average temperature based on lapse rates over operational altitudes should be developed

In the pressure equations a scale height constant H (kilometers) is used to parameterize the exponential ratio. This constant is defined mathematically as:

$$H = \frac{RT_{avg}}{g} \qquad (2.6)$$

The scale height permits a first order pressure approximation based on an average atmospheric temperature and when combined with the ideal gas law can complete a mass balance of a continuous column of atmosphere acting on a cross-section of the earth's surface. The result is the hydrostatic pressure equation.

$$\frac{1}{p}\frac{dp}{dh} = -\frac{g}{RT} \qquad (2.7)$$

This result yields the following differential equation, which when solved provides an estimate of atmospheric pressure.

$$\frac{p}{p_0} = \exp(-\int_0^h \frac{g}{RT} dh) \qquad (2.8)$$

When predicting the atmospheric density scale height the isothermal atmosphere assumption allows the pressure scale height to be used to predict density. The scale heights are related by the expression

$$\frac{1}{H^*} = \frac{1}{H} + \frac{1}{T}\frac{dT}{dh} \qquad (2.9)$$

Again, assuming the temperature lapse rate is zero due to the isothermal assumption the value of H* is simply H.

Being able to relate the density of Earth's atmosphere at a given altitude is an important consideration for sizing an airship hull. As will be discussed later in this section, the density of the air displaced and the associated mass of lifting gas within the hull are critical for predicting the maximum altitude an airship can obtain.

The isothermal temperature assumption is important to the analysis of the airship. The ideal gas law can demonstrate that both pressure and volume relate proportionately to temperature. An increase in temperature will cause a proportional increase in either pressure or volume. This is evident when you take a simple helium party balloon outside on a cold winter day. The balloon can be assumed to be sealed with a constant mass of gas inside of it. When exposed to the cold temperature, the balloon's volume and pressure decrease visibly as it becomes smaller and less rigid. However, when dealing with the large volume of gas present in an airship, the impact of temperature changes in the atmosphere is of small consequence for a first order approximation. Typically the temperature gradient in the first 10 to 15 kilometers of the atmosphere (troposphere) is approximated in a standard atmosphere as -6.5° Celsius/km. Between 10 and 15 kilometers the atmospheric temperature lapse rate goes to zero in a region known as the tropopause. This region can extend as high as 20 kilometers. Above the tropopause is the stratosphere, which is characterized by increasing atmospheric temperatures caused by absorption of solar ultraviolet radiation. The relatively slow changes in heating and cooling of the airship system at high altitudes and its surrounding environment allow it to be considered isothermal in this analysis despite know temperature changes.

2.4.2 Aerostatics

As alluded to earlier, an airship is able to generate lift by taking advantage of the phenomenon that a less dense fluid will rise to a point of equal density. This section seeks to explain the fundamental principles of airship lift and altitude requirements. Key to this section are the principles that lift capacity of an airship is a function of lifting gas mass and airship altitude is a function of the lifting gas volume. These design parameters for an airship are important to understand later when the performance of a damaged airship is being evaluated.

2.4.2.1 Airship Lift

High altitude airships are being pursued for their ability to lift important payloads to great altitudes. They accomplish this by displacing heavy air with a less dense gas that will rise to seek density equilibrium. A mass balance relationship can represent this principle.

$$mg < gV_{air}(\rho_{air} - \rho_{He}) \qquad (2.10)$$

This expression says that as long as the weight of a structure is less than the difference between the weight of air displaced and the gas (in this case helium) displacing it, there will be an upward force generated. This force is known as the buoyant force. For the purpose of this paper, any reference to a lifting gas can be accepted to mean helium, unless specifically noted otherwise. As well, the helium will be considered to be unmixed with air or pure helium.

By understanding the mass balance relationship, it becomes apparent that the maximum weight or "lift capacity" [10:3] of an airship is a function of its lifting gas mass. An airship will rise until its buoyant force is equal to the weight it's lifting (L_n).

$$\mathrm{L_n} = gV_{air}(\rho_{air} - \rho_{He}) \qquad (2.11)$$

A design factor in developing an airship is to ensure that the pressure relationship between the gasses inside and outside the airship hull is not impacted. That is, a constant pressure relationship must be maintained. In the case of an airship, that means a constant overpressure must exist inside the hull. If the pressure relationship is maintained then lifting gas pressure decreases uniformly with atmospheric pressure as the airship rises and the gas is able to expand its volume. As volume increases, gas density in the hull decreases and the buoyant force is maintained. The buoyant force will lift the airship until the hull volume is at a maximum and the pressure relationship between the hull and the environment can no longer be held constant. At this point the airship has reached it maximum or "pressure" altitude. [13:2]

An airship hull or envelope is designed to compensate for increasing lifting gas volume as it rises. Contained within the envelope are bladders containing air that's used as ballast. While on the ground these bladders, known as ballonet are inflated and can occupy as much as 40 percent of the airship's envelope. There are generally two on an airship—one forward to control pitch and one aft to control weight. As the airship begins ascent the ballonet volume decreases as air ballast contained in them is thrown overboard. This allows the lifting gas density to decrease and the airship to rise. The airship will continue to rise until the volume occupied by the lifting gas fills the void left by the air released from the ballonet. When this equilibrium is achieved a pressure height is established. When the ballonets are completely depleted the airship's total pressure height or maximum obtainable altitude is reached. To descend air is pumped into the ballonet thereby decreasing the system's sustainable altitude and the airship descends.

By accepting this design principle, a key assumption is made: the rate of change of the lifting gas density is equal to that of the air displaced. This gives a parameter called the "density ratio" (σ) and relates the density of helium to air at any altitude.

$$\frac{\rho_{air}}{\rho_{air0}} = \sigma = \frac{\rho_{He}}{\rho_{He0}} \qquad (2.12)$$

Since the density rate of change is considered equal and the volume of displaced air in the envelope is the same as the volume of helium present, the net lift equation can be rewritten to demonstrate that lift is a function lifting gas mass present in the envelope.

$$\mathrm{L_n} = m_{He} g\left(\frac{\rho_{air0}}{\rho_{He0}} - 1\right) \qquad (2.13)$$

Lifting gas mass should remain constant within the envelope as the airship rises. If ballonet deflation is controlled properly, the airship will rise to its maximum pressure height and maintain that altitude. If an airship rises above its pressure height the pressure difference will be exceeded and lifting gas will be vented resulting in diminished lift capacity. To prevent this from happening, some ballonet inflation is maintained preventing the airship from reaching its maximum altitude. However, for the purpose of this paper it will be assumed that the ballonets are completely deflated at pressure altitude and the airship maintains a constant altitude while operating prior to sustaining any hull damage.

2.4.2.2 Airship Volume

Pressure height of an airship is a function of the vehicle's hull size. Lifting gas must have sufficient volume to expand and achieve a similar density to the environment surrounding it. Therefore, correctly sizing the vehicle drives the altitude at which it will operate. As previously stated, maximum lifting gas volume is reached when the gas density is allowed to decrease without impacting the pressure differential in the hull. Since density is a ratio of the mass of a gas to its volume, the volume of a lifting gas expanded to the equivalent atmospheric density will provide rapid insight into how big an airship must be. The mass of helium used remains constant and the density of helium can be predicted as a function of altitude by taking advantage of the density ratio. The airship size can be predicted by the following equation.

$$\mathrm{V}_{\max} = \frac{m_{He}}{\sigma_p \rho_{air0}} \qquad (2.14)$$

In this equation σ_p represents the density ratio at the desired maximum altitude and ρ_{air0} is the density of air at sea level. Taking advantage of the density scale height model, the density ratio can be rewritten as a function of altitude:

$$\sigma_p = \frac{\rho_{air\,0} \times \exp(-\frac{h}{H})}{\rho_{air\,0}} \qquad (2.15)$$

Taking advantage of the net lift and volume equations derived, it can be shown how large an airship is required to be in order to perform its mission. It is important to remember that for a first order approximation the lift generated by an airship is proportional to the mass of lifting gas on board, while its maximum altitude is proportional to the airship's hull volume.

By definition a high altitude airship is designed to operate above the normal operating regime of typical aircraft. This altitude is typically above 70,000 feet (21.32 kilometers). In theory this region, which is considered outside the definition of airspace controlled by the Federal Aviation Administration (FAA), extends to the ends of Earth's atmosphere above 300,000 feet. (> 91 kilometers). In reality a high altitude airship would operate between 70,000 and 100,000 feet. This operating altitude drives an airship's size requirement. The reason is that the lifting gas—a constant mass in a sealed hull—requires a large volume to sufficiently decrease density in proportion to its surrounding altitude.

Consider the equation for V_{max} (equation 2.14). The mass of lifting gas is constant based on the total weight of the system's structure and payload. However, the density of the gas in the denominator will decrease with increasing altitude. The result is an increasing volume requirement to allow the density to decrease. Figure 2.5 demonstrates how large an airship's hull volume can become. For example, a vehicle weighing 100,000 kilograms requires a volume in excess of two million cubic meters to

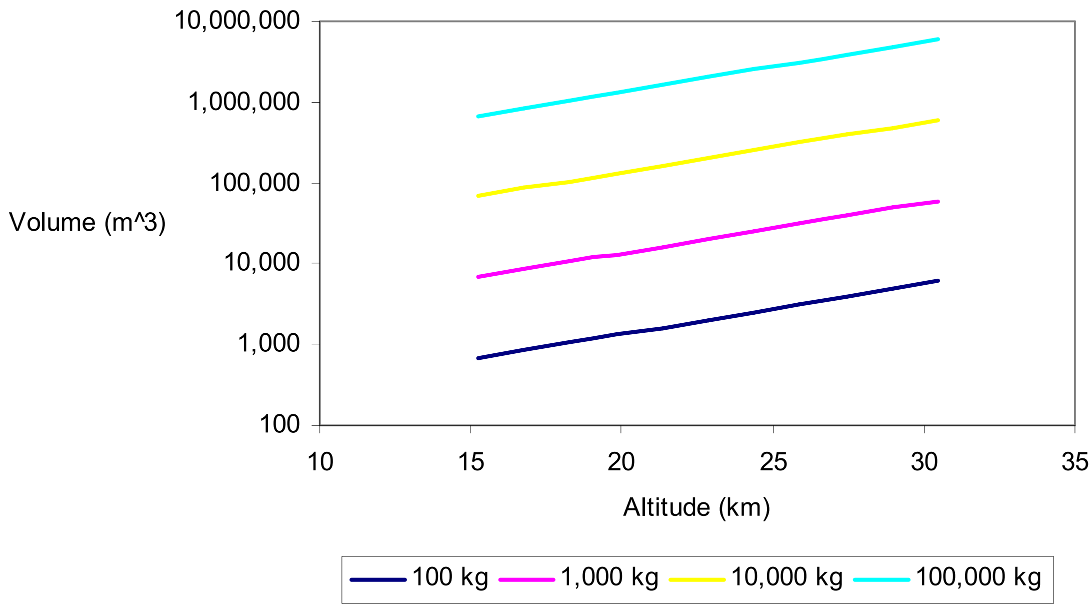


Figure 2.5—Comparison of lifting gas volume required to reach a pressure altitude given a required mass of lifting gas.

reach an altitude of 80,000 feet. That's nearly the size of the Houston Astrodome, which has a diameter of 710 feet and height of 208 feet. It is obvious that sheer size of an airship operating at altitudes nearing 100,000 feet can create difficulties for logistics as well as operation and begin to limit their practicality. However, for lower near space altitudes there remains application.

2.5 Conclusion

The purpose of this section has been to introduce the concepts of airship design and physical principles that enable lift to be generated by controlling rising gases. This basic understanding will enable a look into what occurs when an airship hull is compromised. The vignette introducing this section provided an illustration of a compromised lifting gas hull that seemed to defy the concept that simply puncturing the hull will bring a quick end to the vehicle's flight. The following section will begin to examine what occurs when the hull is compromised and provide initial insights to the question of how much survival time does a vehicle have after being compromised.

3. Methodology

3.1 Chapter Overview

It's important to understand how an airship will perform after having its hull damaged. Upon some analysis, the introductory illustration of a rogue research balloon may or may not be entirely sufficient to describe the performance of a damaged airship. Despite sharing the common thread of using buoyancy to provide lift, the balloon and airship are distinct from each other. Dissimilarities such as propulsion systems and aerodynamic shaping added to an airship begin to show the difference between the two systems. Structural rigidity is also added to the airship design to support the system's performance. This further helps to distinguish the airship from its distant cousin the rogue research balloon.

The objective of this chapter is to develop a methodology for a "first-look" at expected performance of an airship after its lifting gas envelope has been punctured. The illustration has been presented of how Canadian Air Force fighters fired on the rogue balloon as it soared across the Atlantic and unsuccessfully brought its flight to a quick stop. Does the story hold possible similarities for an airship? A model will be developed to look at the question of what impact hull damage has on the survivability of a high-altitude airship. The model can provide planners and operators an estimate of how quickly lift will be lost and what the descent of an airship might look like.

3.2 Courses of Action

As discussed in the previous chapter, for a first-order examination the lift of a lighter-than-air vehicle is dependent primarily on the mass of lifting gas contained in the vehicle’s envelope. If lifting gas is lost then the overall ability of the system to generate lift is degraded. At this point buoyant force generated becomes less than overall system weight and the vehicle begins to descend. The descent rate will be related to the lifting gas mass flow rate, which may be quite small due to the small overpressures required by an airship to maintain its shape and the size of the puncture in its hull. The airship typically has an ellipsoidal geometry to minimize drag forces when moving horizontal or down range and allow better performance of attached propulsion systems. The airship’s flight is unlike that of a weather balloon. A balloon is generally spherical and having no onboard propulsion system, it drifts with prevailing wind currents.

An airship is generally a controlled system that works to optimize the vehicle’s flight. Often control fins are attached to the hull to help direct the vehicle’s heading. As well, the previously discussed ballonet are built into the hull to help control ascent and descent as well as trim the vehicle’s attitude during flight. The weather balloon lacks this sophistication.

The design differences enable different courses of action for an airship when its hull is compromised. In the first case, control is maintained by sacrificing buoyancy, while in the second case buoyancy is preserved longer, but may result in loss of control or ability to steer against the wind. In both cases the end result is a zero-pressure balloon—a hull in which the pressure inside is essentially the same as the atmosphere that surrounds it. Unique methodologies can be developed to study these two cases and provide insights on what might be possible when trying to recover a damaged airship or move it to an advantageous location for flight termination. The remainder of this chapter examines the physical principles that enable analyses.

3.2.1 Case 1: Maintaining Hull Overpressure

The airship uses an internal overpressure in its lifting gas envelope to help maintain the vehicle's shape. Although not large, this overpressure is important to prevent bending moments applied to the hull from "kinking" it. [6:13] As well, the pressure helps prevent nose deformation of the vehicle caused by stagnation pressure on its leading edge. Khoury and Gillett give a design estimate of the overpressure required for a non-rigid airship.

$$\Delta p = 125 + .033 v_{\max}^2 \text{ (units: km/hr)} \qquad (3.1)$$

In the equation, Δp represents the pressure difference between the lifting gas within the hull and the atmospheric pressure at a given altitude. The desire is to maintain a constant Δp as altitude changes in order to maintain airship hull rigidity. It is obvious that airship speed will impact the overpressure so the parameter v appears and should be the additive result of both vehicle's inertial velocity and the speed of any head wind. The overpressure must be designed not only for the speed of the vehicle, but also for the environment in which it will operate.

The essence of this first course of action is to maintain vehicle rigidity following a breech of the hull so that controlled horizontal motion can be attempted. As long as the vehicle maintains its shape the aerodynamic rationale designed into the airship can be exploited at least until overpressure can no longer be maintained. As the vehicle descends it can be steered in a direction that is advantageous to operator's attempt to successfully recover the vehicle or terminate its flight.

The ideal gas law as discussed in chapter two allows us to analyze the descent of the damaged airship. Recall that the law stated that for an ideal gas the product of its volume and pressure is proportional to its mass given an isothermal environment. Since a constant overpressure is maintained in the hull the relationship is simplified to being a relationship of changing volume driving change in lifting gas mass.

To understand the mass change Bernoulli's equation for a compressible fluid is used to begin analysis. Bernoulli's principle states that along a streamline of fluid motion, the mechanical energy per unit mass is conserved. This principle assumes motion of an inviscid and incompressible fluid. Because lifting gasses are compressible, Bernoulli's equation can be modified to accommodate this fact and can be represented as follows.

$$RT\int \frac{dp}{p} + \frac{v^2}{2} + gz = C \qquad (3.2)$$

For this relationship C represents a constant. Since the pressure inside the airship hull is assumed uniform or equal at all points, the potential term is neglected and z is assumed to be zero. The benefit of this relationship is the estimate it provides for lifting gas escape velocity. Using a model of horizontal flow of a fluid from a tank in a free jet, the dynamic pressure can provide an estimate of the escaping fluid's average velocity across a pressure change. [11:122] By integrating the equation and then solving for the velocity an estimate is gained of the average velocity of a lifting gas molecule as it is accelerated from rest inside the hull to some speed as it exits the hull into the atmosphere.

$$v = \sqrt{2RT \ln(\frac{p_{env}}{p_{atm}})} = \sqrt{2RT \ln(1 + \frac{\Delta p}{p_{env}})} \qquad (3.3)$$

In this case p_{env} represents the lifting gas pressure within the hull, while p_{atm} represents the surrounding atmospheric pressure. Because the pressure difference is relatively small between the pressures inside and outside the hull, compressible effects are minimal and satisfactory results could be obtained using the standard Bernoulli equation. By understanding how fast lifting gas escapes from the compromised hull, the mass loss rate can be determined from known quantities.

$$\frac{dm}{dt} = \dot{m} = v\rho_{gas} A \qquad (3.4)$$

A is defined as the area of the puncture in the vehicle's hull. Using the ideal gas equation to represent ρ_{gas} and substituting equation 3.3 in for velocity, the mass loss can be rewritten.

$$\dot{m} = \frac{w_{He} A}{RT}(p_{env})\sqrt{2RT \ln(1 + \frac{\Delta p}{p_{env}})} \qquad (3.5)$$

Once the mass loss rate is determined, solving for gas loss over small time intervals enables the calculation of the volume of displaced air by the hull. Also recall that the volume of lifting gas is equivalent to the volume of displaced air. In the previous chapter it was stated that airship design included ballonet internal to the hull which inflate and maintain internal overpressure as well as change the volume of the lifting gas. Khoury and Gillett suggest that ballonet size can extend to 40 percent the overall hull volume when fully expanded. [6:178] This design principle will be applied to this analysis. Understanding the how lifting gas volume changes, both lifting gas density and air density can be defined for a given time interval and all the information required to complete a mass balance of the system at a given instant is available. A mass balance will provide the descent acceleration the vehicle will experience as lifting gas flows from the hull.

Figure 3.1 illustrates the forces acting on an airship as it begins to descend. Using what we know about lift gas mass, an equation describing acceleration is developed. The ideal gas equation is used to help describe the buoyant force (F_B) and appears in the equation as the ratio of pressures between the atmosphere and the lifting gas. The structural mass (m_s) when multiplied by gravitational acceleration describes the weight contribution of the vehicle to vertical acceleration. Finally, the drag force (F_D) is described in the equation by the atmosphere's density (ρ_{air}) and the vehicle's descent

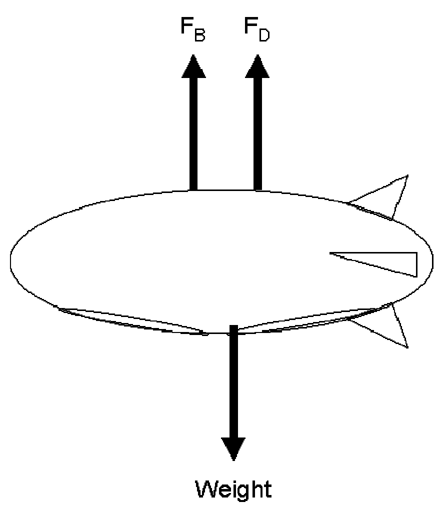


Figure 3.1—Description of forces acting on an airship during descent.

velocity (u) as well as its cross-sectional area (A) and drag coefficient (C_D) normal to the direction of motion.

$$a = \frac{g}{m_{total}}(m_{gas}(\frac{p_{atm}w_{air}}{p_{env}w_{gas}} - 1) - m_s) + \frac{u^2 \rho_{air} A C_D}{2m_{total}} \tag{3.6}$$

The ellipsoidal shape of an airship's hull produces a drag force on the descending vehicle. For simplicity the airship's C_D will be characterized by that of a cylinder (C_D=0.3). [23:418] Once acceleration is understood, all relevant position information about the vehicle can be determined at each time interval. Since the design limit for lifting gas volume expansion is 60 percent of its maximum hull volume based on ballonet size, once this limit is reached the vehicle can no longer maintain constant overpressure. Pressure inside the hull will begin to fall until it reaches atmospheric pressure. At this point the rationale for the current descent analysis becomes invalid and predicting lifting gas loss using the ideal gas law requires that changes in both hull pressure and volume be considered. This methodology is developed in the following case.

3.2.2 Case 2: Hull Pressure Equalization

The analytical advantage of attempting to maintain a constant overpressure within the vehicle's hull is its presentation of only one unknown quantity—volume. Once volume can be defined the analysis proceeds quickly. However, it may be advantageous to allow a damaged airship to descend while the lifting gas pressure decreases with mass loss until it reaches the pressure of the surrounding atmosphere. The rationale for pursuing this case over the constant overpressure case is the decreased loss rate of lifting gas and hence preservation of buoyancy. The implication is that a vehicle may remain at a higher altitude where more favorable wind conditions exist to allow down-range navigation to a suitable recovery/termination location. This case is more similar to the research balloon anecdote than was the previous case. However, significant difference still exists. The main difference is that a hull overpressure still exists with uniform pressure distributed across the envelope. Hence the airship is still capable of sustained navigation according to the overpressure design relationship of Khoury and Gillett.

The analysis for the slow depressurization case depends on the relationship of pressure and volume to help describe mass loss. Previously the ideal gas law was used to demonstrate pressure and volume effects on the airship as it rises. Additionally, it showed how volume and pressure impacted mass loss via an overpressure valve when gas expansion became too great for the hull's size. Mass flow from the hull can be represented by the ideal gas equation by summing the contribution of the volume change at constant pressure and the pressure change at constant volume. This idea is represented in the following equation:

$$\frac{dm}{dt} = \dot{m} = \frac{dp}{dt}\frac{Vw_{gas}}{RT} + \frac{dV}{dt}\rho_{gas} \tag{3.7}$$

The benefit of this relationship is that is helps to understand how pressure and volume change as the airship depressurizes and descends. Mass flow can be defined as previously discussed using the velocity component of the dynamic pressure term in the Bernoulli equation. The mass flow rate can be used in equation (3.7) to determine rates of change for hull pressure and volume as the airship descends.

A difficulty may come in defining the contribution of the differential terms to the total mass loss rate. If a contribution relationship can be established, both the differential changes in pressure and volume can be defined and depressurization can be analyzed. For a first-order approximation it could be assumed that both pressure and volume changes account equally for changes in mass flow. Although it's unlikely these proportions are completely accurate, they can provide sufficient insights into the question of accounting for mass flow. For sake of comparison, the weighting of the pressure and volume effects can be modified. Either portion can be given a greater or lesser weight to study how it might impact the mass flow. The important restriction in applying weighting factors is to ensure that the sum of the factors is exactly one. As a sensitivity test a weighting factor of .33 was given to the pressure change rate and (1-.33) was given to the volume change rate. That is to say that pressure change with time accounted for one-third of the mass flow while the volume change accounted for two-thirds. These values were tested in the descent acceleration equation to determine what impacts exist.

Figure 3.2 compares descent acceleration for the two mass flows cases. Although slightly different in magnitudes the two cases produced very similar acceleration rates. Both show a rapid acceleration downward followed by a deceleration period and then a

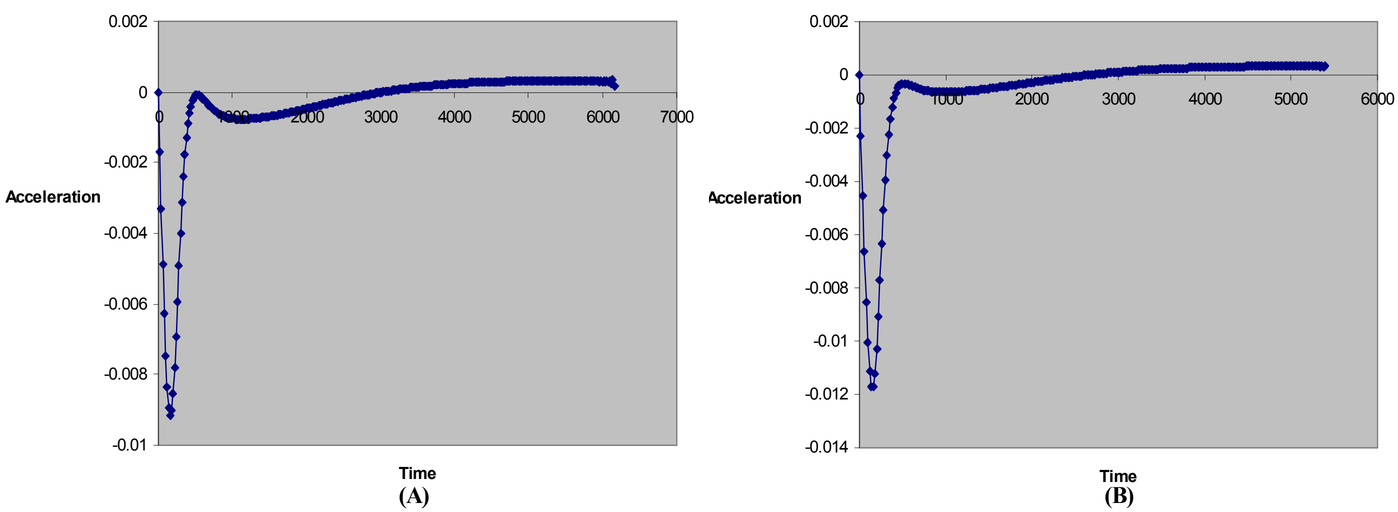


Figure 3.2—Comparison of descent acceleration (m/sec^2) over time (sec) for an airship that has a hull puncture diameter of one foot. In Figure A pressure accounts for approximately one-third lifting gas mass flow escaping from the airship hull and in Figure B pressure accounts for one-half the mass flow.

decrease toward zero as terminal velocity is reached. Although there is some slight difference in peak acceleration between the two sets of proportions, the time impact is small. This comparison of acceleration over time helps to illustrate that varying the weighting factor may not have significant influence on the first-order analysis. Since that is the case, for this analysis we will assume the pressure change rate contributes equally with volume change rate to define mass flow.

Understanding how pressure affects the change in gas mass in the hull enables the calculation of descent acceleration for a damaged airship. Because the mass flow equation provides insight into how the overpressure changes during descent, the same calculation previously used in case one can be reapplied here

Again, acceleration of descent can be calculated and over a given time interval the descent rate and actual descent can be calculated using simple kinematics equations. Unlike the previously discussed case, which required a constant overpressure inside the airship hull to conduct analysis, this case simply requires that an overpressure exist between the hull and the atmosphere. Cross-range velocity and distance can be determined for the depressurizing airship by using Khoury and Gillett's relationship between hull overpressure and cross-range speed. Eventually the hull will depressurize and forward motion will no longer be sustainable. At this point hull pressure will be equal to that of the surrounding atmosphere and any overpressure is exhausted. It's at this point the analysis methodology must change to reflect the new relationship between the hull and atmospheric pressures.

3.2.3 Hull Pressure Reaches Atmospheric Pressure

In both cases previously considered the eventuality for a damaged airship hull is the total loss of any overpressure. This zero-pressure condition is well described by Lewitt in his treatise as a "flabby" airship. [8:86] This condition is most similar to the rogue balloon illustration introduced in the preceding chapter. The airship still contains a certain mass of lifting gas creating a buoyant force. However, the airship has no structural rigidity to neither properly support its payload nor maintain any aerodynamic shaping to assist in horizontal or down-range flight.

Because the pressure ratio between the lifting gas and atmospheric air will be essentially unity, the density of the lifting gas depends solely on atmospheric pressure (continuing on with the isothermal assumption). As the airship descends lifting gas density will increase. If we assume a fairly slow descent (airship not falling like a rock) we can define this process as diffusive and therefore assume the lifting gas and atmospheric gasses are unmixed in the hull. The lighter lifting gas will stratify itself above the heavier atmospheric gases as in Figure 3.3. Since lifting gas is no longer flowing out of the hull, the mass does not change but its volume will decrease and its density will increase.

The bubble of lifting gas that occupies the top portion of the unpressurized hull is subject to "sloshing" similar to a bubble of air trapped underwater. The performance of the airship is limited because its structure is "flabby" and any controlled horizontal motion is difficult develop. It's at this point in the analysis that only descent can be modeled with any confidence and horizontal motion is assumed to be controlled largely by prevailing atmospheric currents.

Descent analysis is straight forward. The ideal gas relationship is used to predict lifting gas density changes as the hull pressure changes. Because the hull pressure is essentially equal to the atmospheric pressure, an atmospheric scale height prediction of pressure provides the necessary insight to complete the analysis. The mass flow is not required for this portion of the descent as we have shown that lifting gas is no longer expelled from the airship as it descends. Since no additional gas is lost the vehicle will maintain a constant buoyant force for the remainder of its descent. However, it will always be less than the vehicle weight and the airship will eventually fall to the ground.

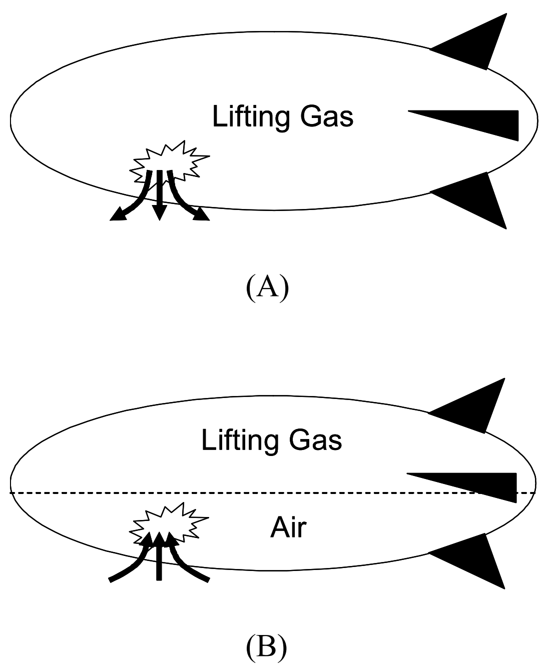


Figure 3.3—Stratification of lifting gas and atmospheric constituents occurs following airship hull pressure equalization. (A) Atmospheric gasses cannot enter hull because of lifting gas overpressure and lifting gas flow out of the hull. (B) Atmospheric gasses begin to enter the airship hull after pressure has equalized resulting in stratified layers of lifting and atmospheric gasses.

Some difficulty will be realized in determining acceleration because of the airship's "flabbiness" during this portion of descent. The coefficient of drag is important to control the velocity of the descent in this case. However, the lack of rigidity in the hull at this point complicates the vehicle's geometry. Previously, a drag coefficient for a flow across a cylinder was used to help estimate drag on the hull during descent. This assumed sufficient overpressure existed within the hull to maintain a geometry roughly similar to a cylinder. The sloshing of the lifting gas bubble inside the hull makes it hard to predict a constant drag coefficient. For the sake of simplicity in this case, a drag coefficient similar to that used previously can be used again in this analysis. By doing this we are neglecting impacts of the sloshing gas bubble has on vehicle's center of gravity and vehicle pitch angle during descent. This approximation assumes stability in the gas bubble and a continued descent with a relatively low pitch angle, symmetric mass distribution about the center of gravity, and no induced horizontal forces causing down range motion other than prevailing atmospheric winds.

An important consideration in this zero-pressure condition is that the gas volume is characterized by a hydrostatic pressure gradient, which previously was absent. Additionally, the location of the hull compromise is an important consideration as it will determine with volume of lifting gas remaining in the damaged hull. Since the capability of navigation is lost at this point, analysis of this condition produces little insight. An airship will drift with the wind, if it is even able to maintain stability following depressurization. Analysis of airship performance after pressure equalization will not be modeled.

3.2.4 Down Range Motion

It's of interest to operators and planners to understand more than how much time is available before an airship reaches a recovery/termination altitude. The first case considered the tactic of maintaining constant hull overpressure for as long as possible. The purpose was to maintain sufficient control of the vehicle to attempt some horizontal motion. Although the vehicle will be descending, in the constant overpressure case some estimate of horizontal distance or range needs to be made.

The simplest analysis is to solve for range covered by finding the product of the vehicle's horizontal velocity component and the time required for hull overpressure to begin to fall. During this time the vehicle will retain sufficient rigidity to maneuver to and assume a down-range course. For further simplicity the vehicle's horizontal velocity component will be assumed constant for the entire period the hull will be able to maintain a constant overpressure.

Khoury and Gillett provide a typical cruise speed range for an airship of 25 to 35 knots. [6:491] This range accounts for airship size, geometry, and also that it is not operating with a damaged hull. Higher speeds are attainable but are highly condition dependent. Considering the high altitude where the vehicle is operating, its large size, and the current challenge of developing propulsion systems to maneuver the airships, an estimate within the previously stated range seems acceptable. Complexities such as changes in hull pressure gradients due to the horizontal acceleration will be neglected and assumed not to exist or contribute to the lifting gas flow rate from the airship. Finally, a down-range estimate will be provided to give initial insights to horizontal distance covered.

3.3 Summary

The case of the rogue research balloon traveling over 4,000 miles has stimulated interest in developing a methodology for studying the descent of a damaged airship. The aim is to develop a method for rapid estimation of how much time is available to move a damaged airship to a recovery/termination location. But the question remains on what is the best course of action to take to move that airship. A constant hull pressure could be maintained to allow some period of controlled flight or the hull pressure could be allowed to fall to zero over some period of time and conserve altitude.

Methodologies were developed to assess both cases—constant overpressure and slow depressurization. Both analyses capture insights that can be taken from the ideal gas equation and Bernoulli's principle and translated into mass balance equations. The constant overpressure case was fairly straight forward to develop because the airship hull pressure was constant in order to maintain vehicle structure. Lifting gas mass flow was easy to calculate because it required only knowing the lifting gas volume change. The case of slow depressurization added complexity. This case required an understanding of both pressure change and volume change to characterize mass flow. Providing a relative contribution factor of pressure change and volume change to the mass flow allows the change in hull pressure during descent to be predicted over small time intervals. By developing these two methodologies an analysis of the optimum course of action for recovery/termination can be performed.

A final portion of the analysis examines what occurs when the hull's overpressure has been depleted and the lifting gas pressure is equal to the atmospheric pressure. Again this case took advantage of a simplifying fact that since lifting gas flow from the hull had ceased when the overpressure equaled zero, volume of gas was the only factor affecting lifting gas density. Thus, as the vehicle descends, the gas density increases and its volume decreases. Since the process is slow it is assumed the lifting gas and atmospheric gases remain stratified with the lighter gas trapped in a "bubble" above the atmospheric gasses. This allows the assumption that lifting gas mass remains constant for this portion of the analysis.

These methods of analysis can provide insights into performance under certain conditions. The intention is to use them to understand relative outcomes and compare their utility. Further exploration of when a constant overpressure or slow pressure equalization course of action is most advantageous is the subject of the following chapter.

4. Results and Analysis

4.1 Chapter Overview

The methods developed in chapter three for analyzing the performance of a high-altitude airship that has sustained damage to it gas envelope were integrated into a model. In this chapter, the model is used to examine airship survivability. It's good to remember the modeling axiom that "every model is wrong; some are useful," as analyses of events are conducted. The goal is not to provide an exact answer predicting exactly how long a vehicle can survive. There are numerous considerations that make it very challenging to provide those types of insights given the broad view of analysis this paper has developed. However, comparative analyses provided by examining two distinct courses of action to follow when an airship hull sustains damage will provide useful insights to help the planner or operator decide what actions to take.

This chapter begins with a review of possible courses of action that might be taken to extend the survivability of an airship. Specific attention will be paid to examining what will occur if the rigidity of an airship is maintained after the hull is compromised. Two questions to be addressed are: how long can the vehicle maintain its required overpressure after being damaged and how far can the vehicle travel while maintaining the structural rigidity required to maintain control surface integrity? A comparative analysis will provide insights regarding how an airship will perform if the hull overpressure is not maintained and the vehicle is allowed to depressurize. Finally, an examination of the isothermal atmosphere assumption will be made to validate the model results. Impacts of atmospheric pressure, density, and temperature lapse rates in the stratosphere and troposphere will be examined and compared.

Ultimately, the comparative analyses should provide recommendations that will be documented in the final section of this paper. Table 4.1 provides an overview of the insights to be developed using data developed by the airship model.

Table 4.1—Analysis questions

Question 1: How long can an airship maintain required pressure to provide the needed rigidity to sustain navigation capability following compromise of its hull?
Questions 2: How far can an airship maneuver following compromise of its hull?
Question 3: How long will it take for an airship to reach pressure equilibrium with the atmosphere following compromise of its hull?
Questions 4: How do atmospheric pressure, density, and temperature lapse rates impact the results of the isothermal model?

4.2 Analyses

4.2.1 Case 1: Maintaining Hull Overpressure

If an airship's hull is damaged allowing lifting gas to escape and depressurization to begin, it might be desirable to attempt to keep the hull pressure at its design pressure for as long as possible. The capability to maintain a constant hull overpressure would enable the airship to retain its design structure and provide integrity to its aerodynamic control surfaces. However, maintaining a constant overpressure would likely increase the loss flow rate of lifting gas resulting in a sacrifice of buoyancy. Eventually the ability to maintain constant overpressure will be lost but the opportunity to control and maneuver the vehicle for a short period might prove advantageous in recovering it or its payload. Methods for maintaining overpressure were discussed in the preceding chapter. The method discussed in this paper was to begin expanding the ballonet contained within the airship's hull until its design limit for inflation is reached. Depending on the size of the hole and the designed overpressure, a mass flow rate for lifting gas loss can be calculated by utilizing Bernoulli's equation and the ideal gas law. The gas loss results in diminished buoyancy. Using Newton's law for motion, characterization of the airship's vertical acceleration can be made.

Currently, the United States Army Space and Missile Defense Command (SMDC) has started an advanced concept technology demonstration to launch an unmanned high altitude airship for a one-month flight. The vehicle will "station-keep" at altitudes above 65,000 feet with the goal of operating a multi-mission sensor/communications suite. SMDC requirements call for the airship to deliver a 500 pound payload to altitude with a cruise speed capability of 20 knots. An artist's rendering of such an airship is shown in Figure 4.1 and additional information is available in Appendix D.

Figure 4.1—Lockheed Martin illustration of its high altitude airship concept vehicle [18]

The requirements for the Army's airship demonstration provide a baseline for developing modeling inputs. Notional operating requirements are required to supply inputs for modeling an airship's survivability. Table 4.2 outlines model inputs used to conduct this analysis of airship survivability. Consistency between inputs is important to

Table 4.2—Airship model inputs

Initial Altitude	21.315 km (70,000 feet)
Structural Mass (vehicle and payload)	1,000 kg
Vehicle Cruise Speed	50 km/hr (30 km/hr speed into a 20 km/hr wind)
Fineness Ratio	4 : 1
Length / Diameter	81 m / 20 m

ensure the integrity of modeling. The modeling will provide data on speed, range, and altitude for an airship while varying the hole size in the lifting gas envelope. Model inputs are notional but are related to requirements for the Army's high-altitude airship program.

The story commonly used to illustrate airship survivability describes a free-floating research balloon that was allegedly shot by Canadian fighter jets. The story alleges as many as 1,000 twenty-millimeter projectiles were fired at the balloon. It is unknown how many actually hit the balloon, but it has to be assumed that some projectiles punctured the balloon's skin. Since this story forms the basis for analysis, the equivalent puncture size of a single projectile forms the initial collection of data from the model. Following on, modeling is made for equivalent hole sizes up to a puncture diameter of three feet. Analysis comprised making comparative measures to determine possible advantages of attempting to maintain a constant overpressure. It has been generally speculated in survivability discussions that a small puncture to an airship's skin would drive a slow escape of lifting gas. The result would be a fairly substantial reaction time to maneuver the airship for navigation down range. The model data for a single puncture of the size of a 20-millimeter projectile validates the idea of a slow process. The time estimate for hull depressurization provides ample time for maneuvering the airship and navigating it down range. The results illustrated in Figure 4.2 provide the model's estimations of the airship's ability to be successfully navigated following a 20-millimeter diameter hull puncture and attempts by operators to maintain a constant overpressure in the hull for as long as possible. Appendix C presents model results for a variety of hole sizes up to a three-foot diameter hole (.91 meter).

Down range velocity for the airship remains constant following a puncture as long as the design overpressure can be maintained. However, speed begins to fall off exponentially when a constant overpressure can no longer be maintained due to complete expansion of ballonet inside the airship hull. The velocity decrease is due to the design relationship between over pressure and the square of the maximum down-range velocity. It was stated empirically that an airship with a small hole in its hull would have some time to maneuver before it is lost and the model bears this out. Model results for a 20 millimeter diameter hole indicate the airship will have approximately 40 hours to maneuver before exhausting its design overpressure. This will provide the airship an

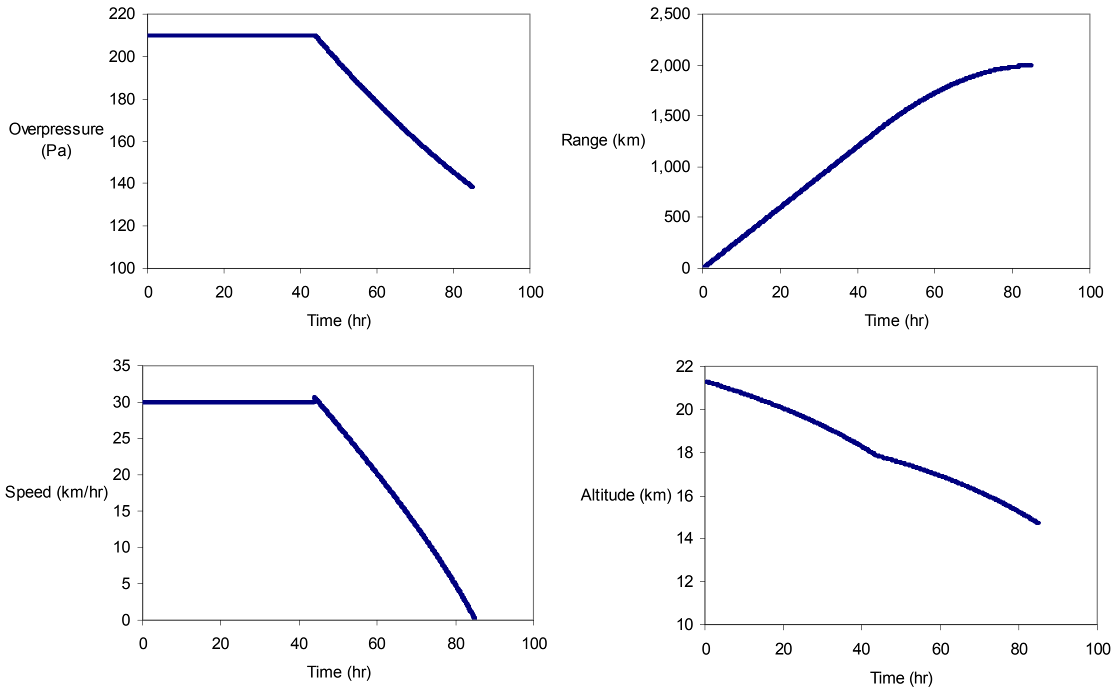


Figure 4.2—Predictions of hull depressurization, down range speed, range, and altitude for an airship with a 20 millimeter diameter hole in its lifting gas envelope.

opportunity to travel toward a recovery location at a constant speed. After losing its design overpressure, the model indicates the airship would have another period nearly as long in which its hull overpressure would decrease until it reaches atmospheric pressure. During that period the airship would be capable of maintaining a continuously decreasing velocity related to its instantaneous overpressure, further extending its possible range. Indications are the airship would have in excess of 80 hours of controllable flight, at least 40 of which would be with the hull at designed overpressure. This would provide operators with nearly 2,000 kilometers of down-range travel to maneuver the airship.

Beyond the point that the airship hull pressure equalizes with the atmospheric pressure, the airship's down-range travel may not terminate. However, it will become difficult to characterize. The hull will lack any aerodynamic integrity to withstand stagnation pressure on its forward edge and lose all capability to maintain its fineness ratio. Model analyses beyond this point are difficult to conduct and it is assumed that at this point the vehicle is no longer capable of controlled flight. Although it remains aloft, it will drift with prevailing winds, which could be considered detrimental to the vehicle recovery operation.

Model results are best used when they are able to provide insights relative to other cases, which would allow comparisons of performance. The same modeling analysis was conducted on an airship that had experienced hull compromises of up to three feet in diameter. Significant decreases in the airship's range capability were noted as the size of the hole in the hull was increased. It seems intuitive to expect that as the hole size is increased depressurization occurs at a faster rate. This is borne out in the model's data as represented by Figure 4.3. The depressurization rate initially appears to increase slowly as the initial hole size increases by a factor of 10. Closely inspecting the resulting data shows that for small holes on the order of less than six inches the range capability falls by an order of magnitude for every three inches of diameter increase. For hole diameters between six inches and one foot the corresponding range decrease is another order of magnitude. Finally, results for hole sizes ranging from one foot to three feet in diameter the range decreases another order of magnitude. This fairly rapid decrease in range capability relative to hole size indicates a need for operators to be able to quickly select a course of action and begin its execution. The airship's range capability as shown in Figure 4.3 reflects the change in depressurization rates. Hole sizes with a diameter

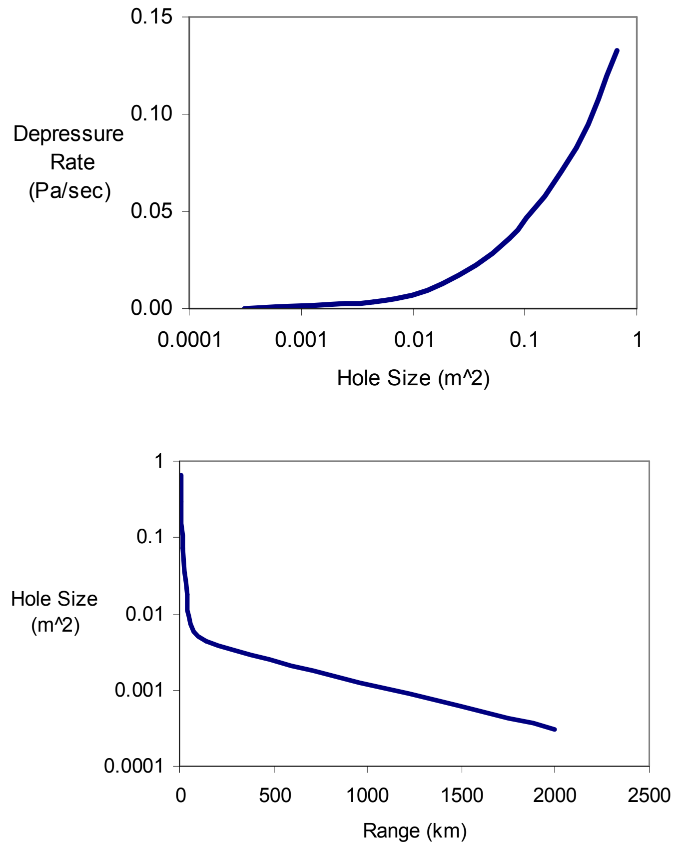


Figure 4.3—Average depressurization rate for the modeled airship and corresponding down-range travel capability for the vehicle given a range of hull puncture sizes.

greater than six inches significantly decrease the possible down-range distance the airship can attain. The airship modeled rapidly loses range when the hole size in its hull exceeds six inches in diameter. As expected the down range distance is shorter for larger holes. However, Figure 4.4 shows an interesting result. An airship that sustains greater damage will maintain a greater altitude at pressure equalization. This altitude difference can be as much as 25 percent for the largest hole size modeled. The reason for this altitude advantage is a shorter time of forced overpressure and the corresponding lower loss of lifting gas mass. Despite significantly shorter down-range travel capabilities, the airship with a greater puncture size can maintain an altitude advantage that may be able to be exploited. The capability to keep an airship at a greater altitude may provide an extended useful life for a system that is not a priority to recover. A disposable communications relay or altitude-tuned sensor may be kept over a location at a more advantageous altitude; something not possible if the vehicle descends too quickly. This altitude advantage could be exploited to minimize or eliminate loss of coverage times experienced while a replacement vehicle is deployed.

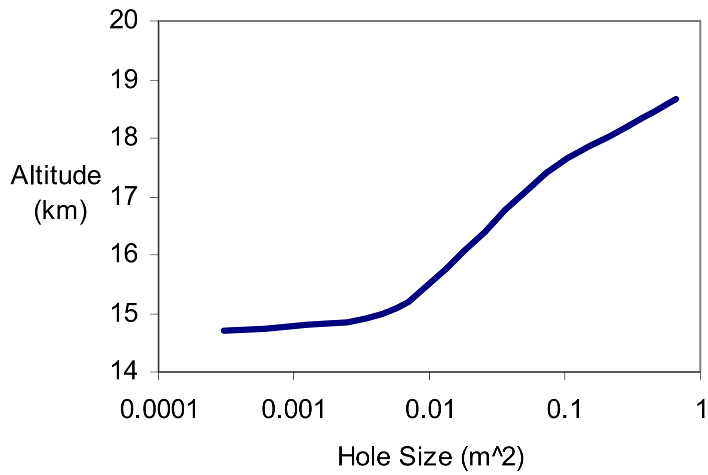


Figure 4.4—Predicted altitude at atmospheric pressure equalization for an airship maintaining constant overpressure for some period following a hull compromise.

As seen in the initial set of performance curves hull depressurization is characterized by two distinct phases: a period of constant overpressure followed by another period of pressure falling to equalize with the surrounding atmosphere. The change in processes is evident by a “knee” in the depressurization curve. In this region beyond the knee in the curve the airship’s hull depressurization process becomes solely based on the instantaneous difference between the envelope and atmospheric pressures. Since the hull pressure is decreasing from its initial design pressure, the velocity the lifting gas is escaping is slower. This can be illustrated using Bernoulli's equation. A larger overpressure will result in a higher average velocity of lifting gas escaping from the hull. It's likely that not attempting to maintain a designed overpressure will result in a slower loss of lifting gas and possibly provide greater attitude capability. It warrants examining the case of allowing the hull to depressurize without attempting to maintain design overpressure.

4.2.2 Case 2: Allowing Hull Depressurization

The natural tendency is for a gas to flow from a region of higher pressure to a region of lower pressure. Simply put, that is the basis for examining case two. If a lifting gas envelope is compromised, the flow of gas will be out of the hull into the atmosphere. This process will continue as long as a pressure difference exists. Case two examines whether the airship's performance would be enhanced by a slower loss of lifting gas by not maintaining hull pressure as in case one. Since buoyancy is a function of lifting gas mass as stated earlier, then there may be some benefit to preserving the amount of lifting gas on board the airship. Case two proposes slowing the loss rate of lifting gas over case one in order to preserve lift.

The same model used to characterize the airship's performance following loss of constant overpressure was applied to this question. The same starting atmospheric parameters and vehicle performance requirements used in case one were used in this portion of the analysis. The analysis included looking at a baseline hull compromise equivalent to a hole made by a 20 millimeter projectile and then ranging it up to three feet in diameter. Figure 4.5 shows the performance characteristics of an airship allowed to undergo depressurization without attempting to maintain its design overpressure. The data is compared with the airship's performance while maintaining a constant overpressure for the same size hole.

As with case one and empirical predictions, allowing the hull to depressurize through a small hole provides a significant period of controllable flight. Interestingly essentially the same time to reach atmospheric pressure equalization within the hull is

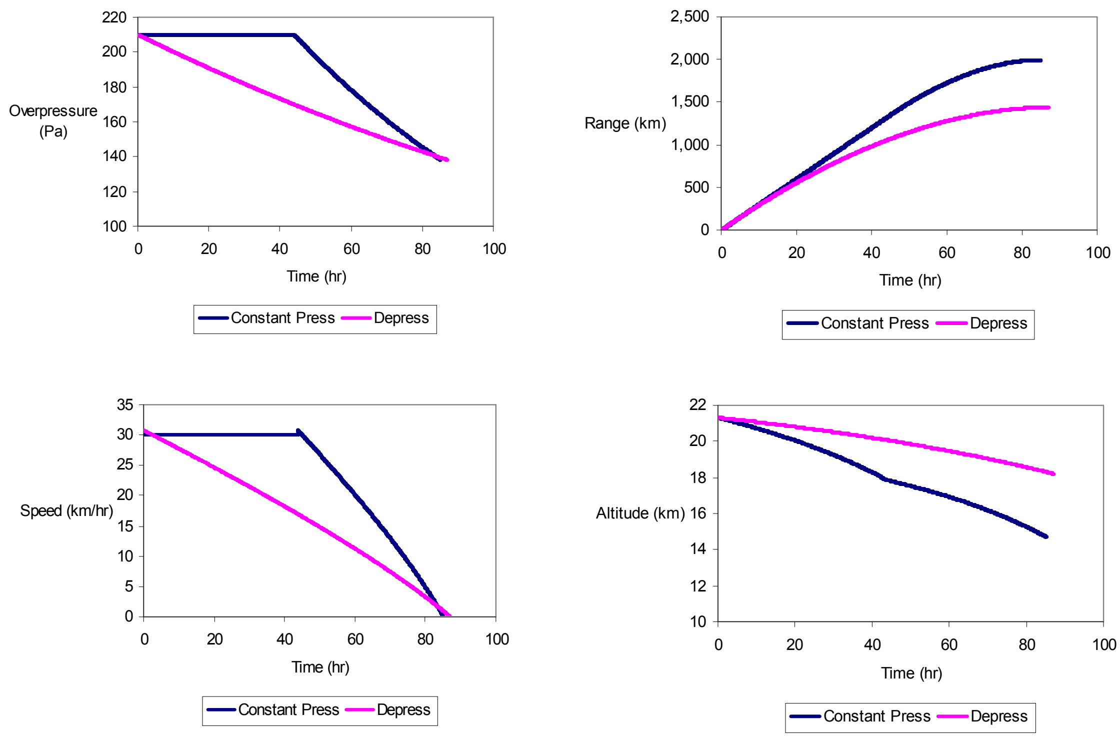


Figure 4.5—Predictions of hull depressurization, down range speed, range, and altitude for an airship with a 20 millimeter diameter hole in its lifting gas envelope. Comparison is made with performance of the airship when a constant overpressure is maintained for some period of time.

noted in both scenarios. However, because velocity is exponentially related to the airship's design overpressure, a significantly lower down-range speed is predicted. The end result is a less favorable prediction of down-range distance when the airship is allowed to slowly depressurize. Distance traveled during slow depressurization is about 27 percent less than distance covered while maintaining a constant overpressure for a 20 millimeter diameter hole. However, as the hole size reaches the upper end of the range modeled, the slowly depressurizing airship covers 85 percent less distance than the airship maintaining constant overpressure. Figure 4.6 shows that for larger hole sizes range capability is improved by attempting to maintain the airship's design overpressure. The advantage of keeping the airship's design overpressure at design level as long as possible is realized in down-range distance capability—especially for larger hole sizes.

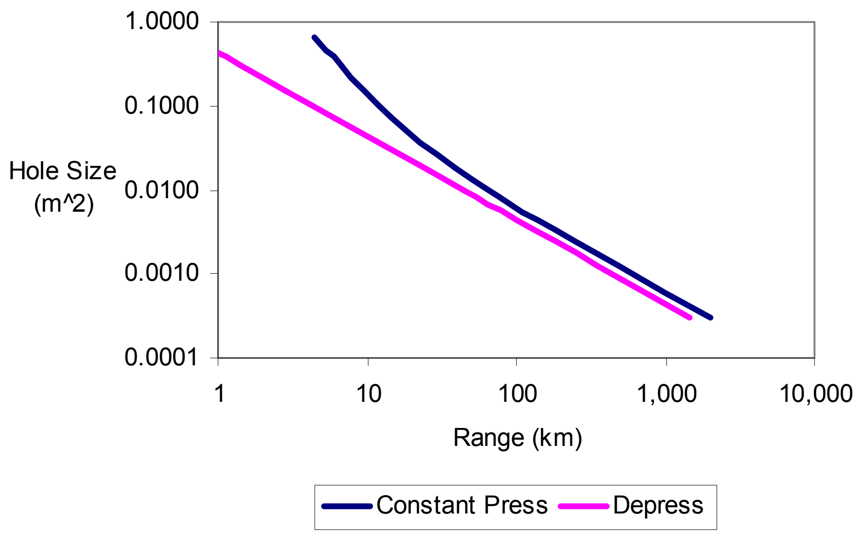


Figure 4.6—Down-range distance capability decreases more rapidly for an airship undergoing slow depressurization than when design overpressure is maintained. This becomes increasingly severe as hole sizes increase.

The advantage of allowing a slow depressurization is in preservation of altitude. Modeling indicates that the airship allowed to undergo slow depressurization retained nearly 20 percent more of its initial altitude than an airship maintaining a constant overpressure. The average descent rate for an airship with a 20 millimeter diameter hole undergoing slow depressurization is .019 meters/second; more than 50 percent slower than the airship that is maintaining a constant overpressure. The slower depressurization drives a smaller lifting gas loss rate than when a constant overpressure is maintained. Attempts to maintain a constant overpressure actually drive an increasing mass flow rate from the hull as shown in Figure 4.7. The increasing rate is due to the greater difference in hull and atmospheric pressure as the airship descends. Conversely, slow depressurization creates a decreasing difference between hull and atmospheric pressure and lifting gas mass is preserved.

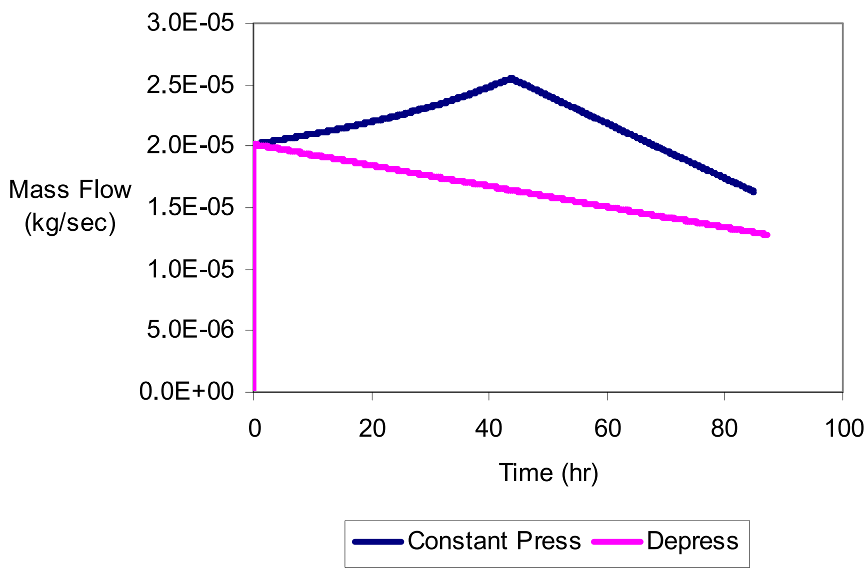


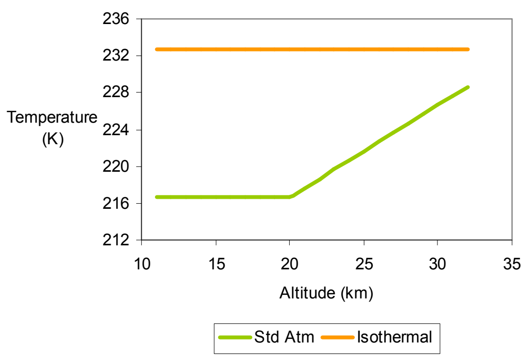
Figure 4.7—Mass flow rate comparisons for the constant pressure and slow depressurization cases. The increasing loss rate for the constant overpressure case is due to increasing pressure differences between hull and atmospheric pressures and results a decreased altitude at atmospheric equalization

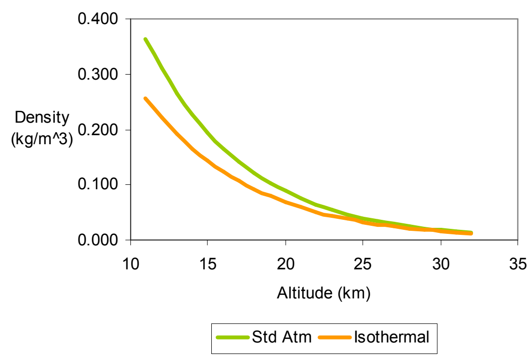
The slower descent rate advantage of allowing depressurization might be beneficial for extending the useful life of a damaged vehicle providing communication or sensor coverage over a specific location. If recovery of the system is not critical and wind conditions are favorable, slow depressurization could allow a system to remain high over a location longer. The advantage is seen as a decrease in the loss of coverage time over a location while a replacement is deployed. This advantage can be exploited for communication relays, which increase line of sight transmissions for radio broadcasts, or for an altitude-tuned sensor that's useful life can be extended by preserving altitude. Additionally, preserving altitude may provide improved range by allowing the vehicle to travel above stronger jet stream winds that exist below 70,000 feet. Despite control surface integrity compromises, less intense head winds may allow an airship to increase its range at a higher altitude.

4.2.3 The Isothermal Assumption

An important assumption made in developing the airship model is the isothermal atmosphere assumption. The airship performance data developed by the model is based on an earth's atmosphere in which its constituents are well mixed and maintain a constant concentration. This type of atmosphere allows the determination of a scale height, which is based on an average temperature within the atmosphere and was discussed in chapter two. As stated earlier, by the ideal gas law pressure is proportional to temperature, so atmospheric pressure can be affected by temperature. Because airship performance is closely related to atmospheric pressure, it is worthwhile to examine the assumption that an atmospheric temperature lapse rate can be neglected in this model.

Atmospheric pressure, temperature, and density lapse rates can be modeled accurately by the US Standard Atmosphere, 1976. This atmospheric model divides the earth's atmosphere into several layers based on altitude extending from sea level to beyond 100 kilometers. [19:21] In each of these atmospheric layers a series of equations characterize the lapse rates for pressure, temperature, and density specific to that layer. The airship modeling was conducted primarily in two of the atmospheric regions—layers two and three. Both layers are defined as the stratosphere by the model. Layer two reaches from 11 kilometers altitude (above sea level) to less than 20 kilometers. This region is characterized by an isothermal layer generally understood meteorologically to have a temperature lapse rate equal to zero. Layer three lies above 20 kilometers to less than 32 kilometers and exhibits an increasing temperature with altitude. Figure 4.8 shows atmospheric temperature, pressure, and density profiles as defined by the Standard Atmosphere model. In the graphs the values are compared with profiles generated using the isothermal assumption.





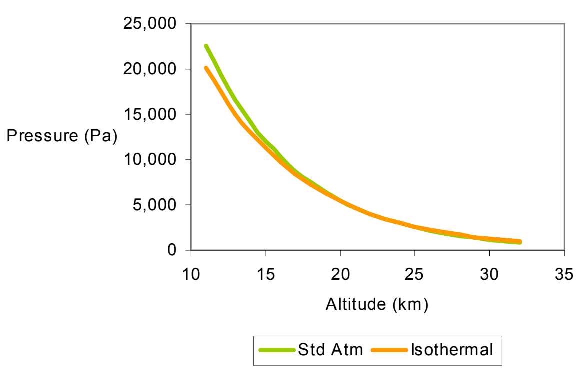


Figure 4.8—Standard Atmosphere model profiles for air temperature, density, and pressure between 11 and 32 kilometers altitude compared with isothermal values.

Mathematical expressions for atmospheric temperature, pressure, and density of a standard atmosphere were inserted into the model in place of their corresponding isothermal atmosphere model value. [15:13] These equations are listed in Appendix A. The model was asked to produce output for an airship under the same conditions as the case one analysis with a corresponding gas envelope hole size equal to a 20 millimeter diameter projectile. The output results are shown in Figure 4.9 as compared to the same scenario assuming isothermal conditions.

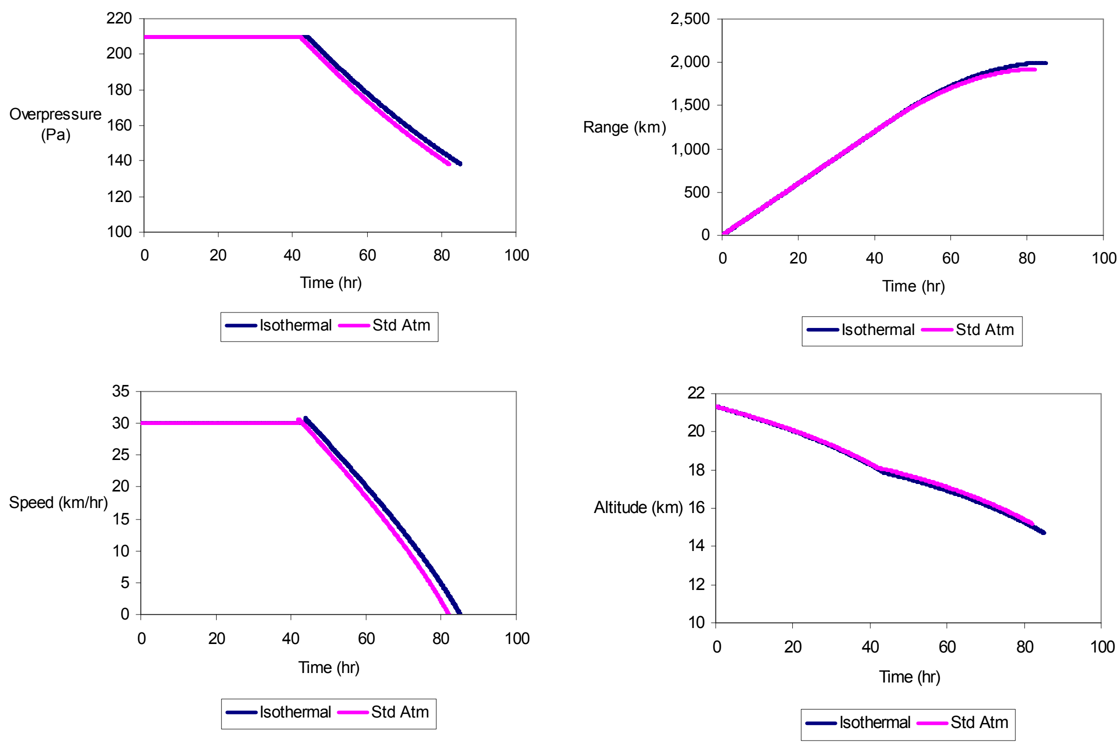


Figure 4.9—Comparison of performance characteristics for an airship modeled in a US Standard Atmosphere 1976 model and an isothermal atmosphere model.

The output using the standard atmosphere provided closely corresponding results, deviating less than 3.5 percent over the controllable flight portion of the airship's depressurization. Differences are likely due to slightly smaller mass flow rates predicted by the standard atmosphere. This is evident from the range and altitude results in Figure 4.9. Lower mass flow rates are evident by the decreased range and increased altitude predictions the model provides for the standard atmosphere.

4.3 Summary

Building on the understanding of airship design, Bernoulli's Principle, the ideal gas law, and atmospheric characteristics, a model was developed to provide data on performance parameters of a damaged airship. Airship design and performance requirements provided predictions on how an airship's survivability is impacted by the damage it sustains. Important maneuver capabilities such as down-range speed, distance, and altitude were characterized as a function of hull overpressure for tailored scenarios. The data developed by the model provided insights on options to pursue to extend the life of a damaged airship.

The robustness of the model was challenged by examining a key atmospheric assumption—that atmospheric temperature effects have minimal impact on a first-order analysis. Using the 1976 US Standard Atmosphere model to develop atmospheric temperature, pressure, and density lapse rates, the model produced data that deviated less than 3.5 percent from the output developed from an isothermal model. The reproduction of such data lends credibility to the assumption that for this analysis the atmospheric effects on airship performance can be modeled assuming an average temperature.

5. Conclusion

5.1 Conclusion

Survivability concerns for a damaged airship have on occasion been anecdotally answered with the 1998 flight of a rogue Canadian research balloon. Is this a fair comparison for survivability of a self-propelled, navigable airship? Critical for the design of an airship is the hull overpressure. It is strongly correlated to an airship's maximum down range velocity. The idea of survivability needs to be well understood as conclusions are made. If airship survivability is tied to the ability to maintain control over the vehicle and its performance, then its survivability must be related to the overpressure of its lifting gas hull. Once the overpressure is depleted the airship is a free-floating vehicle. If survivability is based on the operator's ability to recover the airship or its payload, then only the controllable portion of flight can be considered during analysis.

This chapter synthesizes ideas developed regarding impacts to airship survivability. Understanding airship performance when damage occurs can drive a course of action to take to best utilize a resource. Knowing possible courses of action to take after an airship is damaged can help shed light on what steps to take with a crippled airship.

It seems Thome correctly postulated that a punctured balloon would descend slowly as lifting gas diffuses into the atmosphere. The data produced by the model for both courses of action support his contention. However, in his paper Thome's reference was to a free-floating vehicle and not a navigable airship. Despite modeling support that a damaged balloon may stay aloft several days, its motion would be directed solely by the prevailing wind currents and have no autonomy in setting a course heading or maintaining a position. Viewing survivability without the ability to take positive steps to navigate an airship into a position to recover it and/or its payload is the communication equivalent of sending a message in a bottle at sea. The chance of the message reaching the correct audience is small. Similarly, leaving a damaged airship to float freely as the Canadian research balloon did leaves little guarantee that any hope exists of recovering it or exploiting its remaining capabilities. This is particularly valid in a conflict situation where hostile intentions and sensitive operations can impact the recovery process. Yes, it is possible for an airship to remain aloft for days and travel for thousands of miles as was demonstrated in the research balloon scenario. But, its course and speed can only be passively postulated by meteorological predictions, rather than be positively controlled by an on-board control system. In terms of survivability, the balloon example only provides evidence an airship might be able to stay aloft for significant duration. The application of Thome's example by lighter-than-air proponents to the case of airship survivability has shortcomings that need to be understood quantitatively.

This paper focused on developing a physical model to help understand survivability of an airship. It has added insights on how maneuverable an airship is following a compromise to its lifting gas hull. Through the modeling three valuable insights have been gained. First, it is likely that an airship with a compromised hull will not quickly fall out of the sky, but may stay aloft for a considerable amount of time. However, during only a portion of that time will the airship actually be able to navigate on a heading. Eventually the airship will become free floating, unable to withstand aerodynamic loads caused by moving against atmospheric currents. An interesting model result for the airship is that whether hull overpressure is maintained constant or it is allowed to deflate slowly, the time to reach atmosphere pressure equalization is essentially the same.

Second, an airship can maximize its cross-range distance following damage by attempting to maintain its designed hull overpressure. Using mechanisms such as ballonet inflation, an airship can maintain its design overpressure and sustain for a portion of time its aerodynamic design. Preserving its hull shape and overpressure allows the airship to reach maximum cross-range speeds as suggested by Khoury and Gillett's design relationship between hull pressure and speed. Since a greater average speed is maintained by keeping the pressure constant for some period, down-range distance is improved 28 percent over slow depressurization. In addition, the likelihood of being able to follow the most favorable heading for recovery is increased because the aerodynamic properties of the airship can be preserved. But increased range comes with a price and that is altitude loss. Modeling demonstrates that the longer an airship attempts to maintain a constant overpressure, the greater the loss of altitude. This gives rise to the third insight.

A slowly depressurized airship will retain greater altitude at atmospheric pressure equalization than one that attempts to maintain hull overpressure. Model comparisons suggest that by slowly depressurizing an airship, nearly 20 percent more altitude may be preserved. This may be an important consideration if the desire is to maintain coverage over an area and altitude is an important consideration. Additionally, stronger jet stream winds are typically found at altitudes below 70,000 feet. Preserving altitude and navigating against a lower speed wind in some cases could be advantageous. Despite having a slower speed capability, less head wind could result in a better average cross-range speed and greater distance.

5.2 The Way Ahead

Space Command is working vigorously to set a course for developing methods to utilize near space for the benefit of warfighters. Technical feasibility studies and demonstrations have already shown the benefits of placing a communication relay above a battlefield to extend radio broadcasts over the horizon. Combat Skysat was a successful demonstration by the space battlelab of how communication lines can be extended by placing a radio relay on a balloon and releasing it over the battlefield. Its initial success has set the stage for exploring more options on how to operate in near space. The Missile Defense Agency's attempt to fly a true airship at near space altitudes continues the effort to exploit near space operations. Since these vehicles are carrying important payloads and themselves can be special pieces of equipment, insights need to be developed regarding how to increase their survivability.

Operators and planners value having recovery options that present scenario specific advantages. It is important for high-altitude airship designers to comprehend what occurs when the lifting gas hull is compromised. Likewise, users must expect designers to think through scenarios to ensure the ability to recover or maximize the utility of a damaged airship is explored. This study focuses on a small portion of the survivability question, which is understanding basic options available to the operator or planner once an airship has been damaged. Additional systems work on this topic can include: examining alternative methods for preserving hull overpressure; developing rapid damage assessment processes to assist in survivability course of action selection; or designing an aerial processes for recovering an airship at a designated recovery location. A possible technical topic is computational fluid dynamic modeling of lifting gas escaping from the airship hull in order to validate the use of Bernoulli's equation. Each of these topics will need to be addressed as part of the overall survivability question.

5.3 Summary

This paper provides insights about high-altitude airship survivability. Much is being said about airship survivability, most of it anecdotal. There is no doubt that a damaged lighter-than-air vehicle can travel a great distance despite sustaining damage. A 1998 trans-Atlantic balloon flight example is the most noted. If merely staying aloft is the most important aspect of survivability then the rogue balloon flight is a sufficient example of capability. However, if survivability includes the ability to positively control a vehicle following damage, then a physical assessment is needed.

An airship depends on its lifting gas to maintain altitude. When its gas envelope is compromised and gas flows out the vehicle it will descend. How quickly it descends and where it will no longer be able to be controlled are key questions regarding survivability. Two scenarios were explored in this work: maintaining a constant overpressure to preserve airship aerodynamics; or allowing slow depressurization to maintain altitude. Analysis demonstrates that when an airship maintains a constant overpressure for some period of time following damage, its ability to navigate down range is increased. Alternatively, when the airship is allowed to depressurize slowly it will preserve altitude otherwise lost when a constant pressure is maintained. Eventually, regardless of the course of action taken the airship's hull will equalize with atmospheric pressure. At this point the ability to navigate is lost and the vehicle will be forced to simply drift with atmospheric currents.

Understanding options exist can be important when a war-fighting asset is damaged. Recovering it or maximizing its remaining life can be important strategic decisions. Careful attention needs to be given to the survivability question of high-altitude airships. Continued technical study needs to be conducted on the performance of damaged airships and quantifiable results must accompany anecdotal evidence regarding the question of survivability.

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Appendix A – 1976 United States Standard Atmosphere Model Equations [15:13] [20]

h = altitude above sea level
To = absolute temperature at sea level = 288.15 K
ro = density of air at sea level = 1.225 kg/m^3
Po = standard air pressure at sea level = 101325 Pa

Lapse Rates for Region: 11 km < h < 20 km

$$\text{Temperature (K)} = To(.751865)$$

$$\text{Pressure (Pa)} = Po(.223361)\exp((10999-h)/6341.4)$$

$$\text{Density (kg/m}^3\text{)} = ro(.297076)\exp((10999-h)/6341.4)$$

Lapse Rates for Region: 20 km < h < 32 km

$$\text{Temperature (K)} = To(.682457+h/288136)$$

$$\text{Pressure (Pa)} = Po(.988626+h/198903)^{-34.16319}$$

$$\text{Density (kg/m}^3\text{)} = ro(.978261+h/201010)^{-35.16319}$$

Appendix B – Model Output Data   Case 1 – Constant Overpressure

time inc =	10	sec	mw He =	0.004	kg/mole	R =	8.314	m^3 Pa / mole K		xs area =	1648.36	m^2	rho0 =	1.29
H =	6.82	km	mw air =	0.029	kg/mole	T =	232.68	K		drag coeff =	0.3		speed =	30
p0 =	101325	Pa	gravity =	9.81	m/sec^2	init alt =	70,000	21.315 km		A =	81.2	m		
mass st =	1000	kg	delta p =	210	Pa	area hole =	0.0728	m^2		B =	20.3	m		

time sec	P atm Pa	mass He kg	mass st kg	mass tot kg	accel m/sec^2	v fall m/s	alt km	alt ft	* v He m/sec	* m dot kg/sec	* delta m kg	* vol He m^3	60% vol m^3	Distance km
0	4,450	169	1,000	1,169	0.000	0.000	21.32	70,000	6.75	0.005	0.05	17,520	10,512	0.00
10	4,450	169	1,000	1,169	-0.002	-0.024	21.315	69,999	6.75	0.005	0.05	17,514	CONTINUE	0.08
20	4,450	169	1,000	1,169	-0.005	-0.070	21.314	69,997	6.75	0.005	0.05	17,508	CONTINUE	0.17
30	4,451	169	1,000	1,169	-0.007	-0.140	21.313	69,992	6.75	0.005	0.05	17,499	CONTINUE	0.25
40	4,452	169	1,000	1,169	-0.009	-0.230	21.310	69,985	6.75	0.005	0.05	17,489	CONTINUE	0.33
50	4,453	169	1,000	1,169	-0.011	-0.339	21.307	69,974	6.75	0.005	0.05	17,476	CONTINUE	0.42
60	4,456	169	1,000	1,169	-0.012	-0.461	21.302	69,958	6.75	0.005	0.05	17,460	CONTINUE	0.50
70	4,459	168	1,000	1,168	-0.013	-0.592	21.296	69,939	6.75	0.005	0.05	17,440	CONTINUE	0.58
80	4,462	168	1,000	1,168	-0.013	-0.727	21.289	69,915	6.74	0.005	0.05	17,417	CONTINUE	0.67
90	4,467	168	1,000	1,168	-0.013	-0.859	21.281	69,887	6.74	0.005	0.05	17,392	CONTINUE	0.75
100	4,473	168	1,000	1,168	-0.012	-0.984	21.271	69,855	6.74	0.005	0.05	17,363	CONTINUE	0.83
110	4,479	168	1,000	1,168	-0.011	-1.098	21.260	69,819	6.73	0.005	0.05	17,331	CONTINUE	0.92
120	4,486	168	1,000	1,168	-0.010	-1.200	21.248	69,779	6.73	0.005	0.05	17,297	CONTINUE	1.00
130	4,494	168	1,000	1,168	-0.009	-1.289	21.235	69,737	6.72	0.005	0.05	17,261	CONTINUE	1.08
140	4,503	168	1,000	1,168	-0.008	-1.367	21.221	69,692	6.71	0.005	0.05	17,223	CONTINUE	1.17
150	4,512	168	1,000	1,168	-0.007	-1.434	21.207	69,645	6.71	0.005	0.05	17,184	CONTINUE	1.25
160	4,521	168	1,000	1,168	-0.006	-1.492	21.192	69,596	6.70	0.005	0.05	17,143	CONTINUE	1.33
170	4,531	168	1,000	1,168	-0.005	-1.543	21.177	69,545	6.69	0.005	0.05	17,101	CONTINUE	1.42
180	4,542	168	1,000	1,168	-0.005	-1.589	21.161	69,493	6.69	0.005	0.05	17,058	CONTINUE	1.50
190	4,552	168	1,000	1,168	-0.004	-1.630	21.144	69,439	6.68	0.005	0.05	17,014	CONTINUE	1.58
200	4,563	168	1,000	1,168	-0.004	-1.668	21.128	69,385	6.67	0.005	0.05	16,970	CONTINUE	1.67
210	4,574	168	1,000	1,168	-0.004	-1.703	21.111	69,329	6.66	0.005	0.05	16,925	CONTINUE	1.75
220	4,586	168	1,000	1,168	-0.003	-1.736	21.093	69,272	6.65	0.005	0.05	16,879	CONTINUE	1.83
230	4,597	168	1,000	1,168	-0.003	-1.767	21.076	69,214	6.64	0.005	0.05	16,832	CONTINUE	1.92
240	4,609	168	1,000	1,168	-0.003	-1.797	21.058	69,155	6.64	0.005	0.05	16,785	CONTINUE	2.00
250	4,621	168	1,000	1,168	-0.003	-1.825	21.039	69,095	6.63	0.005	0.05	16,737	CONTINUE	2.08
260	4,634	168	1,000	1,168	-0.003	-1.852	21.021	69,034	6.62	0.005	0.05	16,689	CONTINUE	2.17
270	4,646	168	1,000	1,168	-0.003	-1.878	21.002	68,972	6.61	0.005	0.05	16,640	CONTINUE	2.25
280	4,659	167	1,000	1,167	-0.003	-1.904	20.983	68,910	6.60	0.005	0.05	16,591	CONTINUE	2.33
290	4,672	167	1,000	1,167	-0.002	-1.928	20.964	68,846	6.59	0.005	0.05	16,541	CONTINUE	2.42
300	4,685	167	1,000	1,167	-0.002	-1.952	20.944	68,782	6.58	0.005	0.05	16,491	CONTINUE	2.50
310	4,699	167	1,000	1,167	-0.002	-1.975	20.924	68,718	6.57	0.005	0.05	16,441	CONTINUE	2.58
320	4,713	167	1,000	1,167	-0.002	-1.997	20.905	68,652	6.56	0.005	0.05	16,390	CONTINUE	2.67
330	4,726	167	1,000	1,167	-0.002	-2.019	20.884	68,586	6.55	0.005	0.05	16,339	CONTINUE	2.75
340	4,740	167	1,000	1,167	-0.002	-2.040	20.864	68,519	6.54	0.005	0.05	16,287	CONTINUE	2.83
350	4,755	167	1,000	1,167	-0.002	-2.061	20.843	68,451	6.53	0.005	0.05	16,236	CONTINUE	2.92
360	4,769	167	1,000	1,167	-0.002	-2.081	20.823	68,383	6.52	0.005	0.05	16,183	CONTINUE	3.00
370	4,784	167	1,000	1,167	-0.002	-2.101	20.801	68,314	6.51	0.005	0.05	16,131	CONTINUE	3.08
380	4,798	167	1,000	1,167	-0.002	-2.120	20.780	68,244	6.50	0.005	0.05	16,078	CONTINUE	3.17
390	4,813	167	1,000	1,167	-0.002	-2.139	20.759	68,174	6.49	0.005	0.05	16,025	CONTINUE	3.25
400	4,828	167	1,000	1,167	-0.002	-2.157	20.737	68,103	6.48	0.005	0.05	15,972	CONTINUE	3.33
410	4,844	167	1,000	1,167	-0.002	-2.175	20.716	68,031	6.47	0.005	0.05	15,919	CONTINUE	3.42
420	4,859	167	1,000	1,167	-0.002	-2.193	20.694	67,959	6.46	0.005	0.05	15,865	CONTINUE	3.50
430	4,875	167	1,000	1,167	-0.002	-2.210	20.672	67,887	6.45	0.005	0.05	15,811	CONTINUE	3.58
440	4,891	167	1,000	1,167	-0.002	-2.227	20.649	67,814	6.44	0.005	0.05	15,757	CONTINUE	3.67
450	4,907	167	1,000	1,167	-0.002	-2.244	20.627	67,740	6.43	0.005	0.05	15,703	CONTINUE	3.75
460	4,923	167	1,000	1,167	-0.002	-2.260	20.604	67,666	6.42	0.005	0.05	15,648	CONTINUE	3.83
470	4,939	167	1,000	1,167	-0.002	-2.276	20.581	67,591	6.41	0.005	0.05	15,593	CONTINUE	3.92
480	4,956	167	1,000	1,167	-0.002	-2.292	20.559	67,516	6.40	0.005	0.05	15,539	CONTINUE	4.00
490	4,972	166	1,000	1,166	-0.002	-2.307	20.535	67,440	6.39	0.005	0.05	15,484	CONTINUE	4.08
500	4,989	166	1,000	1,166	-0.002	-2.323	20.512	67,364	6.38	0.005	0.05	15,428	CONTINUE	4.17
510	5,006	166	1,000	1,166	-0.001	-2.338	20.489	67,287	6.37	0.005	0.05	15,373	CONTINUE	4.25
520	5,023	166	1,000	1,166	-0.001	-2.352	20.465	67,210	6.36	0.005	0.05	15,318	CONTINUE	4.33
530	5,041	166	1,000	1,166	-0.001	-2.367	20.442	67,132	6.35	0.005	0.05	15,262	CONTINUE	4.42
540	5,058	166	1,000	1,166	-0.001	-2.381	20.418	67,054	6.33	0.005	0.05	15,206	CONTINUE	4.50
550	5,076	166	1,000	1,166	-0.001	-2.395	20.394	66,975	6.32	0.005	0.05	15,151	CONTINUE	4.58
560	5,094	166	1,000	1,166	-0.001	-2.409	20.370	66,896	6.31	0.005	0.05	15,095	CONTINUE	4.67
570	5,112	166	1,000	1,166	-0.001	-2.423	20.346	66,816	6.30	0.005	0.05	15,039	CONTINUE	4.75
580	5,130	166	1,000	1,166	-0.001	-2.436	20.321	66,736	6.29	0.005	0.05	14,983	CONTINUE	4.83
590	5,148	166	1,000	1,166	-0.001	-2.450	20.297	66,656	6.28	0.005	0.05	14,926	CONTINUE	4.92
600	5,167	166	1,000	1,166	-0.001	-2.463	20.272	66,575	6.27	0.005	0.05	14,870	CONTINUE	5.00
610	5,186	166	1,000	1,166	-0.001	-2.476	20.247	66,494	6.26	0.005	0.05	14,814	CONTINUE	5.08
620	5,204	166	1,000	1,166	-0.001	-2.488	20.222	66,412	6.25	0.005	0.05	14,757	CONTINUE	5.17
630	5,223	166	1,000	1,166	-0.001	-2.501	20.197	66,330	6.23	0.005	0.05	14,701	CONTINUE	5.25
640	5,243	166	1,000	1,166	-0.001	-2.513	20.172	66,247	6.22	0.005	0.05	14,644	CONTINUE	5.33
650	5,262	166	1,000	1,166	-0.001	-2.526	20.147	66,165	6.21	0.005	0.05	14,588	CONTINUE	5.42
660	5,282	166	1,000	1,166	-0.001	-2.538	20.122	66,081	6.20	0.005	0.05	14,531	CONTINUE	5.50
670	5,301	166	1,000	1,166	-0.001	-2.550	20.096	65,997	6.19	0.005	0.05	14,475	CONTINUE	5.58
680	5,321	165	1,000	1,165	-0.001	-2.562	20.071	65,913	6.18	0.005	0.05	14,418	CONTINUE	5.67
690	5,341	165	1,000	1,165	-0.001	-2.573	20.045	65,829	6.16	0.005	0.05	14,361	CONTINUE	5.75
700	5,361	165	1,000	1,165	-0.001	-2.585	20.019	65,744	6.15	0.005	0.05	14,304	CONTINUE	5.83
710	5,382	165	1,000	1,165	-0.001	-2.596	19.993	65,659	6.14	0.005	0.05	14,248	CONTINUE	5.92
720	5,402	165	1,000	1,165	-0.001	-2.608	19.967	65,573	6.13	0.005	0.05	14,191	CONTINUE	6.00
730	5,423	165	1,000	1,165	-0.001	-2.619	19.941	65,487	6.12	0.005	0.05	14,134	CONTINUE	6.08
740	5,444	165	1,000	1,165	-0.001	-2.630	19.914	65,401	6.11	0.005	0.05	14,077	CONTINUE	6.17
750	5,465	165	1,000	1,165	-0.001	-2.641	19.888	65,314	6.09	0.005	0.05	14,020	CONTINUE	6.25
760	5,486	165	1,000	1,165	-0.001	-2.652	19.862	65,227	6.08	0.005	0.05	13,964	CONTINUE	6.33
770	5,507	165	1,000	1,165	-0.001	-2.663	19.835	65,139	6.07	0.005	0.05	13,907	CONTINUE	6.42
780	5,529	165	1,000	1,165	-0.001	-2.673	19.808	65,052	6.06	0.005	0.05	13,850	CONTINUE	6.50
790	5,551	165	1,000	1,165	-0.001	-2.684	19.781	64,963	6.05	0.005	0.05	13,793	CONTINUE	6.58
800	5,572	165	1,000	1,165	-0.001	-2.694	19.754	64,875	6.04	0.005	0.05	13,736	CONTINUE	6.67
810	5,595	165	1,000	1,165	-0.001	-2.705	19.727	64,786	6.02	0.005	0.05	13,679	CONTINUE	6.75
820	5,617	165	1,000	1,165	-0.001	-2.715	19.700	64,697	6.01	0.005	0.05	13,623	CONTINUE	6.83
830	5,639	165	1,000	1,165	-0.001	-2.725	19.673	64,607	6.00	0.005	0.05	13,566	CONTINUE	6.92
840	5,662	165	1,000	1,165	-0.001	-2.735	19.646	64,518	5.99	0.005	0.05	13,509	CONTINUE	7.00
850	5,685	165	1,000	1,165	-0.001	-2.745	19.618	64,427	5.98	0.005	0.05	13,453	CONTINUE	7.08
860	5,707	165	1,000	1,165	-0.001	-2.755	19.591	64,337	5.96	0.005	0.05	13,396	CONTINUE	7.17
870	5,731	164	1,000	1,164	-0.001	-2.765	19.563	64,246	5.95	0.00534	0.05	13,339	CONTINUE	7.25
880	5,754	164	1,000	1,164	-0.001	-2.775	19.535	64,155	5.94	0.005	0.05	13,283	CONTINUE	7.33
890	5,777	164	1,000	1,164	-0.001	-2.784	19.507	64,064	5.93	0.005	0.05	13,226	CONTINUE	7.42
900	5,801	164	1,000	1,164	-0.001	-2.794	19.479	63,972	5.92	0.005	0.05	13,170	CONTINUE	7.50
910	5,825	164	1,000	1,164	-0.001	-2.803	19.451	63,880	5.90	0.005	0.05	13,113	CONTINUE	7.58
920	5,849	164	1,000	1,164	-0.001	-2.813	19.423	63,787	5.89	0.005	0.05	13,057	CONTINUE	7.67
930	5,873	164	1,000	1,164	-0.001	-2.822	19.395	63,695	5.88	0.005	0.05	13,000	CONTINUE	7.75
940	5,897	164	1,000	1,164	-0.001	-2.831	19.367	63,602	5.87	0.005	0.05	12,944	CONTINUE	7.83
950	5,922	164	1,000	1,164	-0.001	-2.841	19.338	63,508	5.85	0.005	0.05	12,888	CONTINUE	7.92
960	5,947	164	1,000	1,164	-0.001	-2.850	19.310	63,415	5.84	0.005	0.05	12,832	CONTINUE	8.00
970	5,971	164	1,000	1,164	-0.001	-2.859	19.281	63,321	5.83	0.005	0.05	12,776	CONTINUE	8.08
980	5,996	164	1,000	1,164	-0.001	-2.868	19.253	63,227	5.82	0.005	0.05	12,720	CONTINUE	8.17
990	6,022	164	1,000	1,164	-0.001	-2.877	19.224	63,132	5.81	0.005	0.05	12,664	CONTINUE	8.25
1000	6,047	164	1,000	1,164	-0.001	-2.886	19.195	63,038	5.79	0.005	0.05	12,608	CONTINUE	8.33
1010	6,073	164	1,000	1,164	-0.001	-2.894	19.166	62,942	5.78	0.005	0.05	12,552	CONTINUE	8.42
1020	6,099	164	1,000	1,164	-0.001	-2.903	19.137	62,847	5.77	0.006	0.06	12,496	CONTINUE	8.50
1030	6,125	164	1,000	1,164	-0.001	-2.912	19.108	62,752	5.76	0.006	0.06	12,441	CONTINUE	8.58
1040	6,151	164	1,000	1,164	-0.001	-2.920	19.079	62,656	5.74	0.006	0.06	12,385	CONTINUE	8.67
1050	6,177	164	1,000	1,164	-0.001	-2.929	19.049	62,559	5.73	0.006	0.06	12,330	CONTINUE	8.75
1060	6,204	163	1,000	1,163	-0.001	-2.937	19.020	62,463	5.72	0.006	0.06	12,274	CONTINUE	8.83
1070	6,231	163	1,000	1,163	-0.001	-2.946	18.991	62,366	5.71	0.006	0.06	12,219	CONTINUE	8.92
1080	6,258	163	1,000	1,163	-0.001	-2.954	18.961	62,269	5.70	0.006	0.06	12,164	CONTINUE	9.00
1090	6,285	163	1,000	1,163	-0.001	-2.962	18.931	62,172	5.68	0.006	0.06	12,108	CONTINUE	9.08
1100	6,312	163	1,000	1,163	-0.001	-2.970	18.902	62,074	5.67	0.006	0.06	12,053	CONTINUE	9.17
1110	6,340	163	1,000	1,163	-0.001	-2.979	18.872	61,977	5.66	0.006	0.06	11,998	CONTINUE	9.25
1120	6,367	163	1,000	1,163	-0.001	-2.987	18.842	61,878	5.65	0.006	0.06	11,944	CONTINUE	9.33
1130	6,395	163	1,000	1,163	-0.001	-2.995	18.812	61,780	5.63	0.006	0.06	11,889	CONTINUE	9.42
1140	6,424	163	1,000	1,163	-0.001	-3.003	18.782	61,682	5.62	0.006	0.06	11,834	CONTINUE	9.50
1150	6,452	163	1,000	1,163	-0.001	-3.011	18.752	61,583	5.61	0.006	0.06	11,780	CONTINUE	9.58
1160	6,480	163	1,000	1,163	-0.001	-3.019	18.722	61,483	5.60	0.006	0.06	11,725	CONTINUE	9.67
1170	6,509	163	1,000	1,163	-0.001	-3.026	18.691	61,384	5.58	0.006	0.06	11,671	CONTINUE	9.75
1180	6,538	163	1,000	1,163	-0.001	-3.034	18.661	61,284	5.57	0.006	0.06	11,616	CONTINUE	9.83
1190	6,567	163	1,000	1,163	-0.001	-3.042	18.631	61,185	5.56	0.006	0.06	11,562	CONTINUE	9.92
1200	6,597	163	1,000	1,163	-0.001	-3.050	18.600	61,084	5.55	0.006	0.06	11,508	CONTINUE	10.00
1210	6,626	163	1,000	1,163	-0.001	-3.057	18.570	60,984	5.53	0.006	0.06	11,454	CONTINUE	10.08
1220	6,656	163	1,000	1,163	-0.001	-3.065	18.539	60,883	5.52	0.006	0.06	11,401	CONTINUE	10.17
1230	6,686	163	1,000	1,163	-0.001	-3.072	18.508	60,782	5.51	0.006	0.06	11,347	CONTINUE	10.25
1240	6,716	162	1,000	1,162	-0.001	-3.080	18.477	60,681	5.50	0.006	0.06	11,293	CONTINUE	10.33
1250	6,747	162	1,000	1,162	-0.001	-3.087	18.447	60,580	5.49	0.006	0.06	11,240	CONTINUE	10.42
1260	6,777	162	1,000	1,162	-0.001	-3.095	18.416	60,478	5.47	0.006	0.06	11,186	CONTINUE	10.50
1270	6,808	162	1,000	1,162	-0.001	-3.102	18.385	60,376	5.46	0.006	0.06	11,133	CONTINUE	10.58
1280	6,839	162	1,000	1,162	-0.001	-3.109	18.354	60,274	5.45	0.006	0.06	11,080	CONTINUE	10.67
1290	6,870	162	1,000	1,162	-0.001	-3.117	18.322	60,172	5.44	0.006	0.06	11,027	CONTINUE	10.75
1300	6,902	162	1,000	1,162	-0.001	-3.124	18.291	60,069	5.42	0.006	0.06	10,974	CONTINUE	10.83
1310	6,933	162	1,000	1,162	-0.001	-3.131	18.260	59,967	5.41	0.006	0.06	10,922	CONTINUE	10.92
1320	6,965	162	1,000	1,162	-0.001	-3.138	18.228	59,863	5.40	0.006	0.06	10,869	CONTINUE	11.00
1330	6,997	162	1,000	1,162	-0.001	-3.145	18.197	59,760	5.39	0.006	0.06	10,817	CONTINUE	11.08
1340	7,030	162	1,000	1,162	-0.001	-3.152	18.165	59,657	5.37	0.006	0.06	10,764	CONTINUE	11.17
1350	7,062	162	1,000	1,162	-0.001	-3.159	18.134	59,553	5.36	0.006	0.06	10,712	CONTINUE	11.25
1360	7,095	162	1,000	1,162	-0.001	-3.166	18.102	59,449	5.35	0.006	0.06	10,660	CONTINUE	11.33
1370	7,128	162	1,000	1,162	-0.001	-3.173	18.070	59,345	5.34	0.006	0.06	10,608	CONTINUE	11.42
1380	7,161	162	1,000	1,162	-0.001	-3.180	18.039	59,240	5.32	0.006	0.06	10,556	CONTINUE	11.50
1390	7,195	162	1,000	1,162	-0.001	-3.187	18.007	59,136	5.31	0.006	0.06	10,505	END	11.58

Case 1 Data (continued)

time inc =	10	sec	mw He =	0.004	kg/mole	R =	8.314	m^3 Pa / mole K		rho0 =		1.29	kg/m^3	xs area =	1648.36	m^2	speed x-range =	30	km/hr
H =	6.82	km	mw air =	0.029	kg/mole	T =	232.68	K		rho0 He =		0.179	kg/m^3	drag coeff =	0.3				
p0 =	101325	Pa	gravity =	9.81	m/sec^2	init alt =	59240	18.03858	km	dp/dt factor		0.5		A =	81.2	m			
mass st =	1000	kg	p op	210	Pa	area hole =	0.0728	m^2		dV/dt factor		0.5		B =	20.3	m			

time	P atm	P env	delta P	P op	mass He	mass tot	vel He	mass flow	delta m	rho He	delta vol	vol	a y	v y	alt	alt	vel x-range	dist x-range
sec	Pa				kg	kg	m/sec	kg/sec	kg	kg/m^3		m^3	m/sec^2	m/sec	km	ft	km/hr	km
1380	7,194.955	7,404.955	0.00	210.0000	165.4425	1,165.443	5.31	0	0	0.015311		10,805.23	0	0	18.039	59,240	30.752	11.5
1390	7,194.955	7,403.630	1.32495	208.6751	165.3833	1,165.383	5.29	0.005920428	0.0592043	0.015309	1.933347	10,803.29	-0.0012573	-0.0125731	18.038	59,240	30.355	11.58
1400	7,195.088	7,402.442	1.32076	207.3543	165.3243	1,165.324	5.28	0.005900665	0.0590067	0.015306	1.927238	10,801.37	-0.0025027	-0.0376002	18.038	59,238	29.956	11.67
1410	7,195.484	7,401.522	1.31656	206.0377	165.2655	1,165.266	5.26	0.005880859	0.0588086	0.015303	1.921112	10,799.44	-0.0037131	-0.0747309	18.037	59,236	29.555	11.75
1420	7,196.273	7,400.998	1.31234	204.7254	165.2069	1,165.207	5.24	0.005860955	0.0586095	0.015300	1.914950	10,797.53	-0.0048484	-0.1232145	18.036	59,232	29.152	11.83
1430	7,197.573	7,400.990	1.30808	203.4173	165.1485	1,165.149	5.23	0.005840903	0.0584090	0.015298	1.908737	10,795.62	-0.0058555	-0.1817694	18.034	59,226	28.747	11.91
1440	7,199.492	7,401.605	1.30378	202.1135	165.0903	1,165.090	5.21	0.005820658	0.0582066	0.015295	1.902458	10,793.72	-0.0066756	-0.2485251	18.032	59,218	28.340	11.99
1450	7,202.116	7,402.930	1.29942	200.8141	165.0323	1,165.032	5.19	0.005800179	0.0580018	0.015292	1.896099	10,791.82	-0.0072548	-0.3210735	18.029	59,207	27.931	12.07
1460	7,205.507	7,405.026	1.29500	199.5191	164.9745	1,164.975	5.17	0.005779435	0.0577944	0.015290	1.889649	10,789.93	-0.0075574	-0.3966470	18.025	59,194	27.520	12.14
1470	7,209.699	7,407.928	1.29051	198.2286	164.9169	1,164.917	5.16	0.005758405	0.0575841	0.015287	1.883103	10,788.05	-0.0075756	-0.4724029	18.020	59,179	27.107	12.22
1480	7,214.695	7,411.637	1.28596	196.9426	164.8595	1,164.860	5.14	0.005737082	0.0573708	0.015284	1.876458	10,786.17	-0.0073350	-0.5457525	18.014	59,161	26.691	12.29
1490	7,220.470	7,416.132	1.28134	195.6613	164.8024	1,164.802	5.12	0.005715468	0.0571547	0.015282	1.869713	10,784.30	-0.0068897	-0.6146490	18.008	59,141	26.274	12.37
1500	7,226.981	7,421.365	1.27665	194.3847	164.7455	1,164.745	5.10	0.005693578	0.0569358	0.015279	1.862876	10,782.44	-0.0063109	-0.6777582	18.002	59,118	25.854	12.44
1510	7,234.166	7,427.279	1.27191	193.1127	164.6887	1,164.689	5.08	0.005671437	0.0567144	0.015276	1.855952	10,780.58	-0.0056721	-0.7344793	17.994	59,094	25.432	12.51
1520	7,241.961	7,433.807	1.26711	191.8456	164.6323	1,164.632	5.06	0.00564907	0.0564907	0.015274	1.848951	10,778.74	-0.0050358	-0.7848370	17.986	59,068	25.007	12.58
1530	7,250.300	7,440.884	1.26226	190.5834	164.5760	1,164.576	5.04	0.00562651	0.0562651	0.015271	1.841883	10,776.89	-0.0044463	-0.8292999	17.978	59,041	24.580	12.65
1540	7,259.122	7,448.448	1.25738	189.3260	164.5200	1,164.520	5.02	0.005603786	0.0560379	0.015269	1.834757	10,775.06	-0.0039287	-0.8685871	17.969	59,013	24.151	12.71
1550	7,268.373	7,456.446	1.25246	188.0735	164.4641	1,164.464	5.00	0.005580925	0.0558092	0.015266	1.827584	10,773.23	-0.0034918	-0.9035048	17.960	58,983	23.719	12.78
1560	7,278.008	7,464.834	1.24752	186.8260	164.4086	1,164.409	4.98	0.00555795	0.0555795	0.015263	1.820369	10,771.41	-0.0031329	-0.9348340	17.951	58,952	23.284	12.84
1570	7,287.991	7,473.575	1.24255	185.5835	164.3532	1,164.353	4.96	0.005534882	0.0553488	0.015261	1.813120	10,769.60	-0.0028432	-0.9632662	17.941	58,921	22.847	12.91
1580	7,298.292	7,482.638	1.23757	184.3459	164.2981	1,164.298	4.94	0.005511738	0.0551174	0.015258	1.805842	10,767.79	-0.0026112	-0.9893785	17.931	58,888	22.407	12.97
1590	7,308.887	7,492.001	1.23256	183.1133	164.2432	1,164.243	4.92	0.005488531	0.0548853	0.015256	1.798541	10,765.99	-0.0024254	-1.0136325	17.921	58,855	21.964	13.03
1600	7,319.758	7,501.644	1.22754	181.8858	164.1886	1,164.189	4.90	0.005465272	0.0546527	0.015253	1.791218	10,764.20	-0.0022754	-1.0363865	17.911	58,821	21.519	13.09
1610	7,330.890	7,511.553	1.22251	180.6633	164.1341	1,164.134	4.88	0.005441971	0.0544197	0.015251	1.783878	10,762.42	-0.0021527	-1.0579135	17.900	58,786	21.070	13.15
1620	7,342.271	7,521.716	1.21747	179.4458	164.0800	1,164.080	4.86	0.005418634	0.0541863	0.015248	1.776523	10,760.64	-0.0020506	-1.0784194	17.890	58,751	20.619	13.21
1630	7,353.890	7,532.123	1.21242	178.2334	164.0260	1,164.026	4.84	0.005395267	0.0539527	0.015246	1.769154	10,758.87	-0.0019639	-1.0980588	17.879	58,715	20.164	13.26
1640	7,365.740	7,542.766	1.20736	177.0260	163.9723	1,163.972	4.82	0.005371877	0.0537188	0.015243	1.761774	10,757.11	-0.0018890	-1.1169485	17.867	58,678	19.706	13.32
1650	7,377.813	7,553.636	1.20230	175.8237	163.9188	1,163.919	4.80	0.005348467	0.0534847	0.015241	1.754383	10,755.36	-0.0018229	-1.1351779	17.856	58,641	19.244	13.37
1660	7,390.103	7,564.730	1.19723	174.6265	163.8655	1,163.866	4.78	0.005325042	0.0532504	0.015238	1.746985	10,753.61	-0.0017638	-1.1528163	17.845	58,603	18.779	13.42
1670	7,402.606	7,576.040	1.19215	173.4343	163.8125	1,163.813	4.76	0.005301605	0.0530160	0.015236	1.739578	10,751.87	-0.0017102	-1.1699186	17.833	58,564	18.311	13.47
1680	7,415.315	7,587.562	1.18707	172.2473	163.7597	1,163.760	4.74	0.005278159	0.0527816	0.015233	1.732165	10,750.14	-0.0016611	-1.1865297	17.821	58,525	17.838	13.52
1690	7,428.227	7,599.293	1.18199	171.0653	163.7072	1,163.707	4.72	0.005254709	0.0525471	0.015231	1.724747	10,748.41	-0.0016157	-1.2026864	17.809	58,486	17.362	13.57
1700	7,441.338	7,611.227	1.17690	169.8884	163.6549	1,163.655	4.70	0.005231255	0.0523126	0.015228	1.717325	10,746.70	-0.0015734	-1.2184203	17.797	58,446	16.882	13.62
1710	7,454.645	7,623.361	1.17181	168.7165	163.6028	1,163.603	4.68	0.005207802	0.0520780	0.015226	1.709899	10,744.99	-0.0015338	-1.2337585	17.784	58,405	16.397	13.66
1720	7,468.142	7,635.692	1.16672	167.5498	163.5510	1,163.551	4.66	0.005184352	0.0518435	0.015224	1.702470	10,743.28	-0.0014966	-1.2487248	17.772	58,364	15.908	13.71
1730	7,481.829	7,648.217	1.16163	166.3882	163.4994	1,163.499	4.64	0.005160906	0.0516091	0.015221	1.695040	10,741.59	-0.0014615	-1.2633402	17.759	58,323	15.415	13.75
1740	7,495.701	7,660.933	1.15654	165.2317	163.4480	1,163.448	4.62	0.005137467	0.0513747	0.015219	1.687608	10,739.90	-0.0014283	-1.2776237	17.747	58,281	14.916	13.79
1750	7,509.756	7,673.837	1.15144	164.0802	163.3968	1,163.397	4.60	0.005114038	0.0511404	0.015216	1.680176	10,738.22	-0.0013969	-1.2915923	17.734	58,238	14.413	13.83
1760	7,523.992	7,686.926	1.14635	162.9339	163.3459	1,163.346	4.58	0.00509062	0.0509062	0.015214	1.672743	10,736.55	-0.0013669	-1.3052617	17.721	58,196	13.904	13.87
1770	7,538.406	7,700.198	1.14126	161.7926	163.2953	1,163.295	4.55	0.005067215	0.0506722	0.015212	1.665312	10,734.88	-0.0013384	-1.3186460	17.707	58,152	13.391	13.91
1780	7,552.995	7,713.652	1.13617	160.6564	163.2448	1,163.245	4.53	0.005043825	0.0504383	0.015209	1.657882	10,733.22	-0.0013112	-1.3317582	17.694	58,109	12.871	13.94
1790	7,567.759	7,727.284	1.13108	159.5254	163.1946	1,163.195	4.51	0.005020452	0.0502045	0.015207	1.650455	10,731.57	-0.0012852	-1.3446104	17.681	58,064	12.345	13.98
1800	7,582.694	7,741.093	1.12599	158.3994	163.1447	1,163.145	4.49	0.004997097	0.0499710	0.015205	1.643030	10,729.93	-0.0012603	-1.3572136	17.667	58,020	11.814	14.01
1810	7,597.799	7,755.077	1.12090	157.2785	163.0949	1,163.095	4.47	0.004973762	0.0497376	0.015202	1.635608	10,728.30	-0.0012365	-1.3695782	17.653	57,975	11.275	14.04
1820	7,613.072	7,769.235	1.11582	156.1627	163.0454	1,163.045	4.45	0.004950449	0.0495045	0.015200	1.628189	10,726.67	-0.0012135	-1.3817137	17.640	57,929	10.730	14.07
1830	7,628.511	7,783.563	1.11074	155.0519	162.9961	1,162.996	4.43	0.004927159	0.0492716	0.015198	1.620775	10,725.05	-0.0011915	-1.3936289	17.626	57,884	10.177	14.10
1840	7,644.116	7,798.062	1.10566	153.9463	162.9471	1,162.947	4.41	0.004903893	0.0490389	0.015195	1.613366	10,723.43	-0.0011703	-1.4053322	17.612	57,838	9.617	14.13
1850	7,659.883	7,812.729	1.10058	152.8457	162.8983	1,162.898	4.39	0.004880653	0.0488065	0.015193	1.605961	10,721.83	-0.0011499	-1.4168313	17.597	57,791	9.048	14.15
1860	7,675.813	7,827.563	1.09551	151.7502	162.8497	1,162.850	4.37	0.004857439	0.0485744	0.015191	1.598563	10,720.23	-0.0011302	-1.4281334	17.583	57,744	8.471	14.18
1870	7,691.903	7,842.563	1.09045	150.6597	162.8014	1,162.801	4.35	0.004834254	0.0483425	0.015189	1.591170	10,718.64	-0.0011112	-1.4392455	17.569	57,697	7.885	14.20
1880	7,708.153	7,857.727	1.08539	149.5743	162.7533	1,162.753	4.33	0.004811099	0.0481110	0.015186	1.583784	10,717.05	-0.0010928	-1.4501737	17.554	57,649	7.289	14.22
1890	7,724.561	7,873.055	1.08033	148.4940	162.7054	1,162.705	4.31	0.004787975	0.0478797	0.015184	1.576404	10,715.48	-0.0010751	-1.4609242	17.540	57,601	6.682	14.24
1900	7,741.125	7,888.544	1.07528	147.4187	162.6577	1,162.658	4.29	0.004764882	0.0476488	0.015182	1.569032	10,713.91	-0.0010578	-1.4715026	17.525	57,553	6.064	14.25
1910	7,757.846	7,904.194	1.07023	146.3485	162.6103	1,162.610	4.27	0.004741822	0.0474182	0.015180	1.561667	10,712.35	-0.0010412	-1.4819143	17.510	57,504	5.435	14.27
1920	7,774.721	7,920.005	1.06519	145.2833	162.5631	1,162.563	4.25	0.004718796	0.0471880	0.015178	1.554310	10,710.79	-0.0010250	-1.4921642	17.495	57,455	4.792	14.28
1930	7,791.750	7,935.973	1.06015	144.2232	162.5162	1,162.516	4.23	0.004695805	0.0469581	0.015175	1.546962	10,709.25	-0.0010093	-1.5022571	17.480	57,406	4.135	14.29
1940	7,808.932	7,952.100	1.05512	143.1680	162.4694	1,162.469	4.21	0.00467285	0.0467285	0.015173	1.539622	10,707.71	-0.0009940	-1.5121976	17.465	57,356	3.464	14.30
1950	7,826.266	7,968.384	1.05010	142.1180	162.4229	1,162.423	4.19	0.004649932	0.0464993	0.015171	1.532291	10,706.17	-0.0009792	-1.5219898	17.450	57,306	2.776	14.31
1960	7,843.751	7,984.824	1.04508	141.0729	162.3767	1,162.377	4.17	0.004627052	0.0462705	0.015169	1.524970	10,704.65	-0.0009648	-1.5316379	17.434	57,256	2.069	14.32
1970	7,861.387	8,001.419	1.04007	140.0328	162.3306	1,162.331	4.15	0.004604211	0.0460421	0.015167	1.517658	10,703.13	-0.0009508	-1.5411456	17.419	57,205	1.343	14.32
1980	7,879.171	8,018.169	1.03506	138.9977	162.2848	1,162.285	4.13	0.00458141	0.0458141	0.015165	1.510357	10,701.62	-0.0009371	-1.5505166	17.404	57,154	0.595	14.32

Case 2 – Slow Depressurization

time inc =	10	sec	mw He =	0.004	kg/mole	R =	8.314	m^3 Pa / mole K	rho0 =	1.29	kg/m^3	xs area =	1648.36	m^2	speed x-range =	30
H =	6.82	km	mw air =	0.029	kg/mole	T =	232.68	K	rho0 He =	0.179	kg/m^3	drag coeff =	0.3			
p0 =	101325	Pa	gravity =	9.81	m/sec^2	init alt =	70000	21.315 km	dp/dt factor	0.5		A =	81.2	m		
mass st =	1000	kg	p op	210	Pa	area hole =	0.0728	m^2	dV/dt factor	0.5		B =	20.3	m		

time	P atm	P env	delta P	P op	mass He	mass tot	vel He	mass flow	delta m	rho He	delta vol	vol	a y	v y	alt	alt	vel x-range	dist x-range
sec	Pa				kg	kg	m/sec	kg/sec	kg	kg/m^3		m^3	m/sec^2	m/sec	km	ft	km/hr	km
0	4,450.278	4,660.278	0.00	210.0000	168.8247	1,168.825	6.75	0	0	0.009636		17,519.97	0	0	21.315	70,000	30.752	0
10	4,450.278	4,659.624	0.65390	209.3461	168.7774	1,168.777	6.74	0.00473765	0.0473765	0.009635	2.458274	17,517.51	-0.0009791	-0.0097907	21.315	70,000	30.556	0.08
20	4,450.342	4,659.035	0.65288	208.6932	168.7301	1,168.730	6.73	0.004729604	0.0472960	0.009633	2.454443	17,515.06	-0.0019493	-0.0292835	21.315	69,999	30.360	0.17
30	4,450.533	4,658.575	0.65185	208.0414	168.6828	1,168.683	6.72	0.004721528	0.0472153	0.009632	2.450596	17,512.60	-0.0028976	-0.0582600	21.314	69,997	30.164	0.25
40	4,450.913	4,658.304	0.65082	207.3906	168.6357	1,168.636	6.71	0.004713388	0.0471339	0.009631	2.446713	17,510.16	-0.0038049	-0.0963088	21.313	69,994	29.967	0.34
50	4,451.542	4,658.283	0.64977	206.7408	168.5887	1,168.589	6.70	0.004705151	0.0470515	0.009629	2.442778	17,507.72	-0.0046465	-0.1427740	21.312	69,989	29.769	0.42
60	4,452.474	4,658.566	0.64871	206.0921	168.5417	1,168.542	6.69	0.004696787	0.0469679	0.009628	2.438776	17,505.28	-0.0053948	-0.1967218	21.310	69,982	29.572	0.50
70	4,453.758	4,659.203	0.64762	205.4444	168.4948	1,168.495	6.68	0.004688268	0.0468827	0.009627	2.434692	17,502.84	-0.0060214	-0.2569357	21.307	69,974	29.373	0.58
80	4,455.437	4,660.235	0.64651	204.7979	168.4480	1,168.448	6.67	0.00467957	0.0467957	0.009625	2.430513	17,500.41	-0.0065010	-0.3219455	21.304	69,963	29.174	0.66
90	4,457.540	4,661.693	0.64537	204.1526	168.4013	1,168.401	6.65	0.004670673	0.0467067	0.009624	2.426229	17,497.99	-0.0068149	-0.3900941	21.300	69,951	28.975	0.74
100	4,460.091	4,663.599	0.64420	203.5084	168.3547	1,168.355	6.64	0.004661561	0.0466156	0.009623	2.421832	17,495.56	-0.0069542	-0.4596362	21.295	69,936	28.775	0.82
110	4,463.098	4,665.963	0.64300	202.8654	168.3082	1,168.308	6.63	0.004652225	0.0465223	0.009621	2.417316	17,493.15	-0.0069221	-0.5288568	21.290	69,918	28.575	0.90
120	4,466.560	4,668.784	0.64177	202.2236	168.2617	1,168.262	6.62	0.004642663	0.0464266	0.009620	2.412681	17,490.73	-0.0067334	-0.5961908	21.284	69,899	28.375	0.98
130	4,470.466	4,672.049	0.64050	201.5831	168.2154	1,168.215	6.60	0.004632878	0.0463288	0.009619	2.407928	17,488.33	-0.0064135	-0.6603256	21.278	69,877	28.174	1.06
140	4,474.797	4,675.741	0.63921	200.9439	168.1692	1,168.169	6.59	0.004622877	0.0462288	0.009617	2.403061	17,485.92	-0.0059943	-0.7202686	21.270	69,853	27.972	1.14
150	4,479.525	4,679.831	0.63789	200.3060	168.1231	1,168.123	6.57	0.004612674	0.0461267	0.009616	2.398087	17,483.52	-0.0055106	-0.7753747	21.263	69,828	27.770	1.22
160	4,484.621	4,684.290	0.63654	199.6695	168.0770	1,168.077	6.56	0.004602284	0.0460228	0.009615	2.393013	17,481.13	-0.0049958	-0.8253322	21.254	69,801	27.568	1.29
170	4,490.051	4,689.086	0.63516	199.0343	168.0311	1,168.031	6.55	0.004591726	0.0459173	0.009613	2.387850	17,478.74	-0.0044787	-0.8701190	21.246	69,772	27.365	1.37
180	4,495.783	4,694.184	0.63377	198.4005	167.9853	1,167.985	6.53	0.004581018	0.0458102	0.009612	2.382607	17,476.36	-0.0039820	-0.9099389	21.237	69,742	27.162	1.44
190	4,501.786	4,699.554	0.63236	197.7682	167.9396	1,167.940	6.52	0.004570178	0.0457018	0.009611	2.377294	17,473.98	-0.0035214	-0.9451532	21.227	69,711	26.958	1.52
200	4,508.029	4,705.166	0.63093	197.1372	167.8940	1,167.894	6.50	0.004559226	0.0455923	0.009610	2.371919	17,471.61	-0.0031063	-0.9762165	21.217	69,679	26.754	1.59
210	4,514.486	4,710.994	0.62948	196.5078	167.8485	1,167.849	6.49	0.004548177	0.0454818	0.009608	2.366493	17,469.25	-0.0027407	-1.0036235	21.207	69,646	26.550	1.67
220	4,521.135	4,717.014	0.62803	195.8797	167.8032	1,167.803	6.47	0.004537047	0.0453705	0.009607	2.361021	17,466.88	-0.0024245	-1.0278686	21.197	69,612	26.345	1.74
230	4,527.954	4,723.207	0.62656	195.2532	167.7579	1,167.758	6.46	0.004525847	0.0452585	0.009606	2.355511	17,464.53	-0.0021551	-1.0494191	21.186	69,578	26.140	1.81
240	4,534.927	4,729.555	0.62509	194.6281	167.7128	1,167.713	6.44	0.00451459	0.0451459	0.009604	2.349969	17,462.18	-0.0019280	-1.0686988	21.176	69,543	25.934	1.88
250	4,542.038	4,736.043	0.62361	194.0045	167.6677	1,167.668	6.43	0.004503285	0.0450329	0.009603	2.344400	17,459.83	-0.0017382	-1.0860803	21.165	69,507	25.728	1.96
260	4,549.277	4,742.660	0.62212	193.3824	167.6228	1,167.623	6.41	0.00449194	0.0449194	0.009602	2.338808	17,457.50	-0.0015804	-1.1018842	21.154	69,471	25.521	2.03
270	4,556.633	4,749.395	0.62063	192.7617	167.5780	1,167.578	6.39	0.004480562	0.0448056	0.009600	2.333197	17,455.16	-0.0014496	-1.1163804	21.143	69,434	25.314	2.10
280	4,564.098	4,756.241	0.61913	192.1426	167.5333	1,167.533	6.38	0.004469157	0.0446916	0.009599	2.327569	17,452.83	-0.0013413	-1.1297937	21.131	69,397	25.107	2.17
290	4,571.665	4,763.190	0.61763	191.5250	167.4887	1,167.489	6.36	0.004457729	0.0445773	0.009598	2.321927	17,450.51	-0.0012515	-1.1423087	21.120	69,360	24.899	2.24
300	4,579.329	4,770.238	0.61612	190.9089	167.4443	1,167.444	6.35	0.004446282	0.0444628	0.009597	2.316272	17,448.20	-0.0011767	-1.1540759	21.109	69,322	24.690	2.30
310	4,587.085	4,777.379	0.61462	190.2942	167.3999	1,167.400	6.33	0.00443482	0.0443482	0.009595	2.310608	17,445.89	-0.0011141	-1.1652173	21.097	69,284	24.482	2.37
320	4,594.929	4,784.610	0.61311	189.6811	167.3557	1,167.356	6.32	0.004423345	0.0442334	0.009594	2.304934	17,443.58	-0.0010614	-1.1758310	21.085	69,245	24.272	2.44
330	4,602.858	4,791.927	0.61160	189.0695	167.3116	1,167.312	6.30	0.004411859	0.0441186	0.009593	2.299253	17,441.28	-0.0010165	-1.1859962	21.073	69,206	24.062	2.51
340	4,610.869	4,799.328	0.61008	188.4594	167.2676	1,167.268	6.29	0.004400365	0.0440037	0.009592	2.293566	17,438.99	-0.0009780	-1.1957766	21.061	69,167	23.852	2.57
350	4,618.960	4,806.811	0.60857	187.8509	167.2237	1,167.224	6.27	0.004388864	0.0438886	0.009590	2.287872	17,436.70	-0.0009447	-1.2052234	21.049	69,127	23.641	2.64
360	4,627.130	4,814.374	0.60705	187.2438	167.1799	1,167.180	6.25	0.004377358	0.0437736	0.009589	2.282173	17,434.42	-0.0009155	-1.2143779	21.037	69,087	23.430	2.70
370	4,635.377	4,822.015	0.60554	186.6383	167.1362	1,167.136	6.24	0.004365848	0.0436585	0.009588	2.276471	17,432.14	-0.0008896	-1.2232739	21.025	69,047	23.218	2.77
380	4,643.698	4,829.733	0.60402	186.0343	167.0927	1,167.093	6.22	0.004354336	0.0435434	0.009587	2.270764	17,429.87	-0.0008665	-1.2319388	21.013	69,007	23.006	2.83
390	4,652.094	4,837.526	0.60250	185.4318	167.0493	1,167.049	6.21	0.004342821	0.0434282	0.009585	2.265054	17,427.61	-0.0008456	-1.2403952	21.000	68,966	22.793	2.90
400	4,660.563	4,845.394	0.60098	184.8308	167.0060	1,167.006	6.19	0.004331306	0.0433131	0.009584	2.259342	17,425.35	-0.0008267	-1.2486619	20.988	68,925	22.580	2.96
410	4,669.104	4,853.335	0.59946	184.2313	166.9628	1,166.963	6.18	0.00431979	0.0431979	0.009583	2.253627	17,423.09	-0.0008093	-1.2567549	20.975	68,884	22.366	3.02
420	4,677.716	4,861.349	0.59794	183.6334	166.9197	1,166.920	6.16	0.004308276	0.0430828	0.009582	2.247911	17,420.84	-0.0007933	-1.2646876	20.962	68,842	22.152	3.08
430	4,686.398	4,869.435	0.59642	183.0370	166.8767	1,166.877	6.14	0.004296763	0.0429676	0.009580	2.242193	17,418.60	-0.0007784	-1.2724715	20.950	68,800	21.937	3.14
440	4,695.150	4,877.592	0.59490	182.4421	166.8339	1,166.834	6.13	0.004285252	0.0428525	0.009579	2.236475	17,416.37	-0.0007645	-1.2801167	20.937	68,758	21.721	3.20
450	4,703.971	4,885.820	0.59338	181.8487	166.7911	1,166.791	6.11	0.004273745	0.0427374	0.009578	2.230755	17,414.14	-0.0007515	-1.2876321	20.924	68,716	21.505	3.26
460	4,712.861	4,894.117	0.59185	181.2568	166.7485	1,166.748	6.10	0.00426224	0.0426224	0.009577	2.225035	17,411.91	-0.0007393	-1.2950253	20.911	68,673	21.289	3.32
470	4,721.818	4,902.485	0.59033	180.6665	166.7060	1,166.706	6.08	0.00425074	0.0425074	0.009575	2.219316	17,409.69	-0.0007278	-1.3023035	20.898	68,631	21.071	3.38
480	4,730.843	4,910.921	0.58881	180.0777	166.6636	1,166.664	6.07	0.004239245	0.0423924	0.009574	2.213596	17,407.48	-0.0007169	-1.3094730	20.885	68,588	20.854	3.44
490	4,739.935	4,919.426	0.58729	179.4904	166.6213	1,166.621	6.05	0.004227754	0.0422775	0.009573	2.207877	17,405.27	-0.0007066	-1.3165395	20.872	68,544	20.635	3.50
500	4,749.094	4,927.999	0.58577	178.9046	166.5792	1,166.579	6.03	0.00421627	0.0421627	0.009572	2.202158	17,403.07	-0.0006969	-1.3235083	20.859	68,501	20.416	3.55
510	4,758.319	4,936.640	0.58425	178.3204	166.5371	1,166.537	6.02	0.004204791	0.0420479	0.009571	2.196441	17,400.87	-0.0006876	-1.3303841	20.845	68,457	20.197	3.61
520	4,767.611	4,945.348	0.58273	177.7377	166.4952	1,166.495	6.00	0.004193319	0.0419332	0.009569	2.190725	17,398.68	-0.0006787	-1.3371716	20.832	68,413	19.976	3.66
530	4,776.967	4,954.124	0.58121	177.1565	166.4534	1,166.453	5.99	0.004181854	0.0418185	0.009568	2.185010	17,396.50	-0.0006703	-1.3438747	20.818	68,369	19.755	3.72
540	4,786.390	4,962.967	0.57969	176.5768	166.4117	1,166.412	5.97	0.004170396	0.0417040	0.009567	2.179297	17,394.32	-0.0006623	-1.3504974	20.805	68,325	19.534	3.77
550	4,795.877	4,971.876	0.57817	175.9986	166.3701	1,166.370	5.96	0.004158946	0.0415895	0.009566	2.173586	17,392.14	-0.0006546	-1.3570433	20.791	68,280	19.312	3.83
560	4,805.429	4,980.851	0.57665	175.4219	166.3286	1,166.329	5.94	0.004147504	0.0414750	0.009565	2.167877	17,389.97	-0.0006472	-1.3635156	20.778	68,236	19.089	3.88
570	4,815.047	4,989.893	0.57513	174.8468	166.2872	1,166.287	5.92	0.004136071	0.0413607	0.009563	2.162171	17,387.81	-0.0006402	-1.3699175	20.764	68,191	18.865	3.93
580	4,824.728	4,999.001	0.57362	174.2732	166.2460	1,166.246	5.91	0.004124646	0.0412465	0.009562	2.156467	17,385.66	-0.0006334	-1.3762520	20.750	68,145	18.641	3.98
590	4,834.474	5,008.175	0.57210	173.7011	166.2048	1,166.205	5.89	0.004113231	0.0411323	0.009561	2.150765	17,383.51	-0.0006270	-1.3825217	20.736	68,100	18.416	4.04
600	4,844.284	5,017.415	0.57058	173.1305	166.1638	1,166.164	5.88	0.004101825	0.0410183	0.009560	2.145067	17,381.36	-0.0006208	-1.3887294	20.723	68,054	18.190	4.09
610	4,854.159	5,026.720	0.56907	172.5614	166.1229	1,166.123	5.86	0.004090429	0.0409043	0.009559	2.139371	17,379.22	-0.0006148	-1.3948775	20.709	68,009	17.964	4.14
620	4,864.097	5,036.091	0.56755	171.9939	166.0821	1,166.082	5.85	0.004079043	0.0407904	0.009558	2.133679	17,377.09	-0.0006091	-1.4009681	20.695	67,963	17.737	4.18
630	4,874.099	5,045.527	0.56604	171.4279	166.0415	1,166.041	5.83	0.004067668	0.0406767	0.009556	2.127990	17,374.96	-0.0006035	-1.4070036	20.681	67,916	17.509	4.23
640	4,884.165	5,055.028	0.56453	170.8633	166.0009	1,166.001	5.81	0.004056303	0.0405630	0.009555	2.122304	17,372.84	-0.0005982	-1.4129859	20.666	67,870	17.280	4.28
650	4,894.294	5,064.595	0.56302	170.3003	165.9604	1,165.960	5.80	0.00404495	0.0404495	0.009554	2.116623	17,370.72	-0.0005931	-1.4189170	20.652	67,823	17.050	4.33
660	4,904.488	5,074.227	0.56151	169.7388	165.9201	1,165.920	5.78	0.004033607	0.0403361	0.009553	2.110945	17,368.61	-0.0005882	-1.4247987	20.638	67,777	16.820	4.38
670	4,914.745	5,083.923	0.56000	169.1788	165.8799	1,165.880	5.77	0.004022276	0.0402228	0.009552	2.105270	17,366.50	-0.0005834	-1.4306327	20.624	67,730	16.589	4.42
680	4,925.065	5,093.685	0.55849	168.6203	165.8398	1,165.840	5.75	0.004010957	0.0401096	0.009551	2.099600	17,364.40	-0.0005788	-1.4364206	20.609	67,682	16.357	4.47
690	4,935.449	5,103.513	0.55698	168.0633	165.7998	1,165.800	5.74	0.003999649	0.0399965	0.009549	2.093935	17,362.31	-0.0005743	-1.4421640	20.595	67,635	16.124	4.51
700	4,945.897	5,113.405	0.55548	167.5079	165.7599	1,165.760	5.72	0.003988354	0.0398835	0.009548	2.088273	17,360.22	-0.0005700	-1.4478644	20.580	67,587	15.890	4.56
710	4,956.408	5,123.362	0.55397	166.9539	165.7201	1,165.720	5.71	0.003977072	0.0397707	0.009547	2.082616	17,358.14	-0.0005659	-1.4535230	20.566	67,540	15.656	4.60
720	4,966.983	5,133.384	0.55247	166.4014	165.6805	1,165.680	5.69	0.003965802	0.0396580	0.009546	2.076964	17,356.06	-0.0005618	-1.4591412	20.551	67,492	15.420	4.64
730	4,977.621	5,143.471	0.55097	165.8504	165.6409	1,165.641	5.67	0.003954544	0.0395454	0.009545	2.071316	17,353.99	-0.0005579	-1.4647203	20.537	67,444	15.184	4.68
740	4,988.323	5,153.624	0.54946	165.3010	165.6015	1,165.601	5.66	0.0039433	0.0394330	0.009544	2.065673	17,351.93	-0.0005541	-1.4702614	20.522	67,395	14.946	4.73
750	4,999.088	5,163.841	0.54796	164.7530	165.5622	1,165.562	5.64	0.003932069	0.0393207	0.009543	2.060035	17,349.87	-0.0005504	-1.4757655	20.507	67,347	14.708	4.77
760	5,009.917	5,174.124	0.54647	164.2066	165.5230	1,165.523	5.63	0.003920852	0.0392085	0.009541	2.054402	17,347.81	-0.0005468	-1.4812339	20.492	67,298	14.468	4.81
770	5,020.810	5,184.472	0.54497	163.6616	165.4839	1,165.484	5.61	0.003909648	0.0390965	0.009540	2.048774	17,345.76	-0.0005433	-1.4866674	20.477	67,250	14.228	4.85
780	5,031.767	5,194.885	0.54347	163.1181	165.4449	1,165.445	5.60	0.003898458	0.0389846	0.009539	2.043152	17,343.72	-0.0005400	-1.4920669	20.463	67,200	13.987	4.89
790	5,042.787	5,205.363	0.54198	162.5761	165.4060	1,165.406	5.58	0.003887282	0.0388728	0.009538	2.037535	17,341.68	-0.0005367	-1.4974335	20.448	67,151	13.744	4.92
800	5,053.872	5,215.907	0.54049	162.0356	165.3672	1,165.367	5.57	0.003876121	0.0387612	0.009537	2.031923	17,339.65	-0.0005334	-1.5027679	20.433	67,102	13.501	4.96
810	5,065.020	5,226.517	0.53900	161.4966	165.3286	1,165.329	5.55	0.003864973	0.0386497	0.009536	2.026317	17,337.62	-0.0005303	-1.5080709	20.417	67,052	13.256	5.00
820	5,076.232	5,237.192	0.53751	160.9591	165.2901	1,165.290	5.54	0.003853841	0.0385384	0.009535	2.020716	17,335.60	-0.0005272	-1.5133433	20.402	67,003	13.010	5.03
830	5,087.509	5,247.932	0.53602	160.4231	165.2516	1,165.252	5.52	0.003842722	0.0384272	0.009534	2.015121	17,333.59	-0.0005243	-1.5185858	20.387	66,953	12.763	5.07
840	5,098.850	5,258.738	0.53453	159.8886	165.2133	1,165.213	5.51	0.003831619	0.0383162	0.009533	2.009533	17,331.58	-0.0005213	-1.5237992	20.372	66,903	12.515	5.10
850	5,110.255	5,269.610	0.53305	159.3555	165.1751	1,165.175	5.49	0.003820531	0.0382053	0.009531	2.003950	17,329.57	-0.0005185	-1.5289839	20.357	66,853	12.266	5.14
860	5,121.724	5,280.548	0.53156	158.8240	165.1370	1,165.137	5.47	0.003809458	0.0380946	0.009530	1.998373	17,327.58	-0.0005157	-1.5341407	20.341	66,802	12.015	5.17
870	5,133.259	5,291.553	0.53008	158.2939	165.0990	1,165.099	5.46	0.0037984	0.0379840	0.009529	1.992802	17,325.58	-0.0005129	-1.5392702	20.326	66,752	11.763	5.20
880	5,144.857	5,302.623	0.52860	157.7653	165.0612	1,165.061	5.44	0.003787358	0.0378736	0.009528	1.987237	17,323.60	-0.0005103	-1.5443728	20.310	66,701	11.510	5.24
890	5,156.521	5,313.759	0.52712	157.2382	165.0234	1,165.023	5.43	0.003776331	0.0377633	0.009527	1.981679	17,321.61	-0.0005076	-1.5494491	20.295	66,650	11.256	5.27
900	5,168.250	5,324.962	0.52565	156.7125	164.9857	1,164.986	5.41	0.00376532	0.0376532	0.009526	1.976127	17,319.64	-0.0005051	-1.5544997	20.279	66,599	11.000	5.30
910	5,180.043	5,336.231	0.52417	156.1884	164.9482	1,164.948	5.40	0.003754325	0.0375433	0.009525	1.970581	17,317.67	-0.0005025	-1.5595249	20.264	66,548	10.743	5.33
920	5,191.902	5,347.568	0.52270	155.6657	164.9108	1,164.911	5.38	0.003743346	0.0374335	0.009524	1.965042	17,315.70	-0.0005000	-1.5645252	20.248	66,496	10.484	5.36
930	5,203.826	5,358.970	0.52122	155.1444	164.8734	1,164.873	5.37	0.003732383	0.0373238	0.009523	1.959509	17,313.74	-0.0004976	-1.5695011	20.232	66,445	10.224	5.39
940	5,215.815	5,370.440	0.51976	154.6247	164.8362	1,164.836	5.35	0.003721437	0.0372144	0.009522	1.953984	17,311.79	-0.0004952	-1.5744529	20.217	66,393	9.962	5.41
950	5,227.870	5,381.977	0.51829	154.1064	164.7991	1,164.799	5.34	0.003710506	0.0371051	0.009521	1.948464	17,309.84	-0.0004928	-1.5793810	20.201	66,341	9.699	5.44
960	5,239.991	5,393.581	0.51682	153.5896	164.7621	1,164.762	5.32	0.003699593	0.0369959	0.009519	1.942952	17,307.90	-0.0004905	-1.5842858	20.185	66,289	9.434	5.47
970	5,252.178	5,405.252	0.51536	153.0742	164.7252	1,164.725	5.31	0.003688696	0.0368870	0.009518	1.937447	17,305.96	-0.0004882	-1.5891676	20.169	66,237	9.167	5.49
980	5,264.430	5,416.991	0.51389	152.5603	164.6885	1,164.688	5.29	0.003677815	0.0367782	0.009517	1.931948	17,304.03	-0.0004859	-1.5940267	20.153	66,185	8.899	5.52
990	5,276.749	5,428.797	0.51243	152.0479	164.6518	1,164.652	5.28	0.003666952	0.0366695	0.009516	1.926457	17,302.10	-0.0004837	-1.5988634	20.137	66,132	8.629	5.54
1000	5,289.135	5,440.671	0.51097	151.5369	164.6152	1,164.615	5.26	0.003656106	0.0365611	0.009515	1.920972	17,300.18	-0.0004815	-1.6036780	20.121	66,080	8.358	5.56
1010	5,301.586	5,452.614	0.50952	151.0274	164.5788	1,164.579	5.25	0.003645276	0.0364528	0.009514	1.915495	17,298.26	-0.0004793	-1.6084708	20.105	66,027	8.084	5.59
1020	5,314.105	5,464.624	0.50806	150.5193	164.5424	1,164.542	5.23	0.003634464	0.0363446	0.009513	1.910025	17,296.35	-0.0004771	-1.6132420	20.089	65,974	7.809	5.61
1030	5,326.690	5,476.702	0.50661	150.0127	164.5062	1,164.506	5.22	0.00362367	0.0362367	0.009512	1.904563	17,294.45	-0.0004750	-1.6179918	20.073	65,921	7.531	5.63
1040	5,339.342	5,488.849	0.50516	149.5076	164.4701	1,164.470	5.20	0.003612892	0.0361289	0.009511	1.899107	17,292.55	-0.0004729	-1.6227205	20.057	65,867	7.252	5.65
1050	5,352.061	5,501.065	0.50371	149.0039	164.4340	1,164.434	5.19	0.003602133	0.0360213	0.009510	1.893660	17,290.66	-0.0004708	-1.6274283	20.040	65,814	6.970	5.67
1060	5,364.848	5,513.349	0.50226	148.5016	164.3981	1,164.398	5.17	0.00359139	0.0359139	0.009509	1.888219	17,288.77	-0.0004687	-1.6321154	20.024	65,760	6.687	5.69
1070	5,377.702	5,525.703	0.50082	148.0008	164.3623	1,164.362	5.16	0.003580666	0.0358067	0.009508	1.882786	17,286.89	-0.0004667	-1.6367819	20.008	65,707	6.401	5.70
1080	5,390.624	5,538.125	0.49937	147.5014	164.3266	1,164.327	5.14	0.00356996	0.0356996	0.009507	1.877361	17,285.01	-0.0004646	-1.6414281	19.991	65,653	6.112	5.72
1090	5,403.614	5,550.617	0.49793	147.0035	164.2910	1,164.291	5.13	0.003559271	0.0355927	0.009506	1.871944	17,283.14	-0.0004626	-1.6460540	19.975	65,599	5.822	5.74
1100	5,416.671	5,563.178	0.49649	146.5070	164.2555	1,164.256	5.11	0.0035486	0.0354860	0.009505	1.866534	17,281.27	-0.0004606	-1.6506599	19.958	65,544	5.529	5.75
1110	5,429.797	5,575.809	0.49506	146.0119	164.2202	1,164.220	5.10	0.003537948	0.0353795	0.009504	1.861132	17,279.41	-0.0004586	-1.6552459	19.942	65,490	5.233	5.77
1120	5,442.992	5,588.510	0.49362	145.5183	164.1849	1,164.185	5.08	0.003527314	0.0352731	0.009503	1.855737	17,277.55	-0.0004566	-1.6598121	19.925	65,436	4.935	5.78
1130	5,456.255	5,601.281	0.49219	145.0261	164.1497	1,164.150	5.07	0.003516698	0.0351670	0.009502	1.850351	17,275.70	-0.0004547	-1.6643587	19.908	65,381	4.634	5.79
1140	5,469.586	5,614.122	0.49076	144.5354	164.1147	1,164.115	5.05	0.003506101	0.0350610	0.009501	1.844973	17,273.86	-0.0004527	-1.6688857	19.892	65,326	4.331	5.81
1150	5,482.987	5,627.033	0.48933	144.0460	164.0797	1,164.080	5.04	0.003495522	0.0349552	0.009500	1.839602	17,272.02	-0.0004508	-1.6733933	19.875	65,271	4.024	5.82
1160	5,496.457	5,640.015	0.48790	143.5581	164.0449	1,164.045	5.02	0.003484961	0.0348496	0.009499	1.834240	17,270.18	-0.0004488	-1.6778815	19.858	65,216	3.714	5.83
1170	5,509.996	5,653.068	0.48648	143.0717	164.0101	1,164.010	5.01	0.00347442	0.0347442	0.009498	1.828886	17,268.36	-0.0004469	-1.6823504	19.841	65,161	3.401	5.84
1180	5,523.605	5,666.192	0.48506	142.5866	163.9755	1,163.975	5.00	0.003463897	0.0346390	0.009497	1.823540	17,266.53	-0.0004450	-1.6868002	19.825	65,105	3.085	5.85
1190	5,537.283	5,679.386	0.48364	142.1030	163.9409	1,163.941	4.98	0.003453393	0.0345339	0.009496	1.818202	17,264.71	-0.0004431	-1.6912309	19.808	65,050	2.766	5.85
1200	5,551.032	5,692.653	0.48222	141.6207	163.9065	1,163.907	4.97	0.003442908	0.0344291	0.009495	1.812873	17,262.90	-0.0004412	-1.6956425	19.791	64,994	2.442	5.86
1210	5,564.851	5,705.990	0.48080	141.1399	163.8722	1,163.872	4.95	0.003432442	0.0343244	0.009494	1.807552	17,261.09	-0.0004393	-1.7000352	19.774	64,938	2.115	5.87
1220	5,578.739	5,719.400	0.47939	140.6605	163.8380	1,163.838	4.94	0.003421994	0.0342199	0.009493	1.802239	17,259.29	-0.0004374	-1.7044089	19.757	64,882	1.784	5.87
1230	5,592.699	5,732.881	0.47798	140.1826	163.8039	1,163.804	4.92	0.003411567	0.0341157	0.009492	1.796935	17,257.49	-0.0004355	-1.7087638	19.740	64,826	1.449	5.88
1240	5,606.729	5,746.435	0.47657	139.7060	163.7698	1,163.770	4.91	0.003401158	0.0340116	0.009491	1.791639	17,255.70	-0.0004336	-1.7130999	19.722	64,770	1.110	5.88
1250	5,620.830	5,760.061	0.47517	139.2308	163.7359	1,163.736	4.89	0.003390769	0.0339077	0.009490	1.786351	17,253.92	-0.0004317	-1.7174172	19.705	64,714	0.766	5.88
1260	5,635.002	5,773.760	0.47376	138.7571	163.7021	1,163.702	4.88	0.003380399	0.0338040	0.009489	1.781073	17,252.14	-0.0004299	-1.7217157	19.688	64,657	0.418	5.88
1270	5,649.246	5,787.531	0.47236	138.2847	163.6684	1,163.668	4.86	0.003370048	0.0337005	0.009488	1.775802	17,250.36	-0.0004280	-1.7259955	19.671	64,600	0.064	5.88

Isothermal Assumption Test Data

time inc =	10	sec	mw He =	0.004	kg/mole	R =	8.314	m^3 Pa / mole K		xs area =	1648.36	m^2	rho0 =	1.225	kg/m^3
H =	6.82	km	mw air =	0.029	kg/mole	T0 =	288.15	K		drag coeff =	0.3		speed =	30	km/hr
p0 =	101325	Pa	gravity =	9.81	m/sec^2	init alt =	70,000		21.315 km	A =	81.2	m			
mass st =	1000	kg	delta p =	210	Pa	area hole =	0.0728	m^2		B =	20.3	m			

									*	*	*	*					
time	P atm	mass He	mass st	mass tot	accel	v fall	alt	alt	v He	m dot	delta m	vol He	60% vol	Dist x-ran	alt	rho air	Temp
sec	Pa	kg	kg	kg	m/sec^2	m/s	km	ft	m/sec	kg/sec	kg	m^3	m^3	km	m	kg/m^3	K
0	4,452	169	1,000	1,169	0.00000	0.000	21.32	70,000	6.54	0.00490	0.04896	16,407	9,844	0.00	21315	0.071148	217.966
10	4,452	169	1,000	1,169	-0.00243	-0.024	21.315	69,999	6.54	0.004896	0.04896	16,402	CONTINUE	0.08	21314.76	0.071148	217.966
20	4,452	169	1,000	1,169	-0.004842	-0.07276	21.314	69,997	6.54	0.004896	0.04896	16,397	CONTINUE	0.17	21314.03	0.071151	217.9658
30	4,452	169	1,000	1,169	-0.007156	-0.144	21.313	69,992	6.53	0.004896	0.04896	16,390	CONTINUE	0.25	21312.59	0.071159	217.965
40	4,453	169	1,000	1,169	-0.009257	-0.237	21.310	69,984	6.53	0.004897	0.04897	16,382	CONTINUE	0.33	21310.22	0.071176	217.9636
50	4,455	169	1,000	1,169	-0.010997	-0.347	21.307	69,973	6.53	0.004897	0.04897	16,371	CONTINUE	0.42	21306.75	0.071203	217.9612
60	4,457	169	1,000	1,169	-0.012226	-0.469	21.302	69,957	6.53	0.004899	0.04899	16,358	CONTINUE	0.50	21302.06	0.071243	217.9578
70	4,461	168	1,000	1,168	-0.012834	-0.597	21.296	69,938	6.53	0.004900	0.04900	16,341	CONTINUE	0.58	21296.08	0.071297	217.9531
80	4,465	168	1,000	1,168	-0.012792	-0.725	21.289	69,914	6.53	0.004902	0.04902	16,321	CONTINUE	0.67	21288.83	0.071365	217.9471
90	4,470	168	1,000	1,168	-0.012171	-0.847	21.280	69,886	6.52	0.004905	0.04905	16,298	CONTINUE	0.75	21280.36	0.071449	217.9398
100	4,476	168	1,000	1,168	-0.011125	-0.958	21.271	69,855	6.52	0.004908	0.04908	16,272	CONTINUE	0.83	21270.78	0.071547	217.9314
110	4,483	168	1,000	1,168	-0.009853	-1.057	21.260	69,820	6.51	0.004912	0.04912	16,243	CONTINUE	0.92	21260.21	0.071657	217.9218
120	4,490	168	1,000	1,168	-0.008540	-1.142	21.249	69,783	6.51	0.004915	0.04915	16,212	CONTINUE	1.00	21248.78	0.07178	217.9112
130	4,498	168	1,000	1,168	-0.007322	-1.215	21.237	69,743	6.50	0.004920	0.04920	16,179	CONTINUE	1.08	21236.63	0.071912	217.8998
140	4,507	168	1,000	1,168	-0.006276	-1.278	21.224	69,701	6.49	0.004924	0.04924	16,144	CONTINUE	1.17	21223.85	0.072053	217.8876
150	4,516	168	1,000	1,168	-0.005425	-1.332	21.211	69,657	6.49	0.004929	0.04929	16,107	CONTINUE	1.25	21210.52	0.072202	217.8749
160	4,525	168	1,000	1,168	-0.004756	-1.380	21.197	69,612	6.48	0.004933	0.04933	16,069	CONTINUE	1.33	21196.72	0.072358	217.8615
170	4,535	168	1,000	1,168	-0.004241	-1.422	21.182	69,565	6.47	0.004938	0.04938	16,031	CONTINUE	1.42	21182.5	0.072519	217.8477
180	4,545	168	1,000	1,168	-0.003847	-1.461	21.168	69,517	6.47	0.004944	0.04944	15,991	CONTINUE	1.50	21167.89	0.072686	217.8335
190	4,556	168	1,000	1,168	-0.003543	-1.496	21.153	69,468	6.46	0.004949	0.04949	15,950	CONTINUE	1.58	21152.92	0.072857	217.8189
200	4,566	168	1,000	1,168	-0.003306	-1.529	21.138	69,418	6.45	0.004954	0.04954	15,908	CONTINUE	1.67	21137.63	0.073034	217.8039
210	4,577	168	1,000	1,168	-0.003115	-1.561	21.122	69,366	6.44	0.004960	0.04960	15,866	CONTINUE	1.75	21122.02	0.073214	217.7886
220	4,588	168	1,000	1,168	-0.002957	-1.590	21.106	69,314	6.43	0.004966	0.04966	15,823	CONTINUE	1.83	21106.12	0.073399	217.773
230	4,600	168	1,000	1,168	-0.002824	-1.618	21.090	69,261	6.43	0.004972	0.04972	15,780	CONTINUE	1.92	21089.94	0.073588	217.7571
240	4,612	168	1,000	1,168	-0.002708	-1.645	21.073	69,207	6.42	0.004978	0.04978	15,736	CONTINUE	2.00	21073.48	0.07378	217.7409
250	4,623	168	1,000	1,168	-0.002606	-1.672	21.057	69,152	6.41	0.004984	0.04984	15,691	CONTINUE	2.08	21056.77	0.073976	217.7245
260	4,636	168	1,000	1,168	-0.002513	-1.697	21.040	69,096	6.40	0.004990	0.04990	15,646	CONTINUE	2.17	21039.8	0.074176	217.7078
270	4,648	167	1,000	1,167	-0.002429	-1.721	21.023	69,040	6.39	0.004996	0.04996	15,600	CONTINUE	2.25	21022.59	0.07438	217.6908
280	4,661	167	1,000	1,167	-0.002352	-1.744	21.005	68,982	6.38	0.005002	0.05002	15,554	CONTINUE	2.33	21005.15	0.074587	217.6736
290	4,673	167	1,000	1,167	-0.002280	-1.767	20.987	68,924	6.37	0.005009	0.05009	15,507	CONTINUE	2.42	20987.48	0.074798	217.6562
300	4,686	167	1,000	1,167	-0.002213	-1.789	20.970	68,866	6.36	0.005015	0.05015	15,460	CONTINUE	2.50	20969.58	0.075011	217.6385
310	4,700	167	1,000	1,167	-0.002151	-1.811	20.951	68,806	6.36	0.005022	0.05022	15,413	CONTINUE	2.58	20951.47	0.075229	217.6206
320	4,713	167	1,000	1,167	-0.002092	-1.832	20.933	68,746	6.35	0.005029	0.05029	15,365	CONTINUE	2.67	20933.16	0.075449	217.6025
330	4,726	167	1,000	1,167	-0.002037	-1.852	20.915	68,685	6.34	0.005036	0.05036	15,317	CONTINUE	2.75	20914.63	0.075673	217.5842
340	4,740	167	1,000	1,167	-0.001985	-1.872	20.896	68,624	6.33	0.005043	0.05043	15,268	CONTINUE	2.83	20895.91	0.0759	217.5656
350	4,754	167	1,000	1,167	-0.001936	-1.891	20.877	68,562	6.32	0.005050	0.05050	15,220	CONTINUE	2.92	20877	0.07613	217.5469
360	4,768	167	1,000	1,167	-0.001889	-1.910	20.858	68,499	6.31	0.005057	0.05057	15,171	CONTINUE	3.00	20857.9	0.076363	217.528
370	4,783	167	1,000	1,167	-0.001845	-1.929	20.839	68,436	6.30	0.005064	0.05064	15,121	CONTINUE	3.08	20838.61	0.076599	217.5089
380	4,797	167	1,000	1,167	-0.001804	-1.947	20.819	68,372	6.29	0.005071	0.05071	15,071	CONTINUE	3.17	20819.14	0.076838	217.4896
390	4,812	167	1,000	1,167	-0.001764	-1.964	20.799	68,307	6.28	0.005078	0.05078	15,021	CONTINUE	3.25	20799.5	0.07708	217.4701
400	4,827	167	1,000	1,167	-0.001726	-1.982	20.780	68,242	6.27	0.005086	0.05086	14,971	CONTINUE	3.33	20779.68	0.077326	217.4505
410	4,842	167	1,000	1,167	-0.001690	-1.999	20.760	68,176	6.26	0.005093	0.05093	14,921	CONTINUE	3.42	20759.7	0.077574	217.4307
420	4,857	167	1,000	1,167	-0.001655	-2.015	20.740	68,110	6.25	0.005101	0.05101	14,870	CONTINUE	3.50	20739.55	0.077825	217.4107
430	4,872	167	1,000	1,167	-0.001622	-2.031	20.719	68,043	6.24	0.005109	0.05109	14,819	CONTINUE	3.58	20719.23	0.078079	217.3905
440	4,888	167	1,000	1,167	-0.001591	-2.047	20.699	67,976	6.23	0.005116	0.05116	14,768	CONTINUE	3.67	20698.76	0.078336	217.3702
450	4,904	167	1,000	1,167	-0.001561	-2.063	20.678	67,908	6.22	0.005124	0.05124	14,716	CONTINUE	3.75	20678.13	0.078596	217.3497
460	4,920	167	1,000	1,167	-0.001532	-2.078	20.657	67,840	6.21	0.005132	0.05132	14,665	CONTINUE	3.83	20657.35	0.078859	217.3291
470	4,936	166	1,000	1,166	-0.001504	-2.093	20.636	67,771	6.20	0.005140	0.05140	14,613	CONTINUE	3.92	20636.42	0.079124	217.3083
480	4,952	166	1,000	1,166	-0.001477	-2.108	20.615	67,702	6.19	0.005148	0.05148	14,561	CONTINUE	4.00	20615.34	0.079393	217.2874
490	4,969	166	1,000	1,166	-0.001452	-2.122	20.594	67,633	6.18	0.005156	0.05156	14,509	CONTINUE	4.08	20594.11	0.079664	217.2663
500	4,985	166	1,000	1,166	-0.001427	-2.137	20.573	67,562	6.17	0.005164	0.05164	14,456	CONTINUE	4.17	20572.74	0.079938	217.2451
510	5,002	166	1,000	1,166	-0.001403	-2.151	20.551	67,492	6.16	0.005172	0.05172	14,404	CONTINUE	4.25	20551.24	0.080215	217.2237
520	5,019	166	1,000	1,166	-0.001380	-2.165	20.530	67,421	6.14	0.005181	0.05181	14,351	CONTINUE	4.33	20529.59	0.080495	217.2022
530	5,036	166	1,000	1,166	-0.001358	-2.178	20.508	67,349	6.13	0.005189	0.05189	14,299	CONTINUE	4.42	20507.81	0.080778	217.1806
540	5,053	166	1,000	1,166	-0.001337	-2.192	20.486	67,277	6.12	0.005198	0.05198	14,246	CONTINUE	4.50	20485.89	0.081063	217.1588
550	5,071	166	1,000	1,166	-0.001316	-2.205	20.464	67,205	6.11	0.005206	0.05206	14,193	CONTINUE	4.58	20463.85	0.081351	217.1369
560	5,088	166	1,000	1,166	-0.001297	-2.218	20.442	67,132	6.10	0.005215	0.05215	14,140	CONTINUE	4.67	20441.67	0.081642	217.1148
570	5,106	166	1,000	1,166	-0.001277	-2.230	20.419	67,059	6.09	0.005223	0.05223	14,087	CONTINUE	4.75	20419.36	0.081936	217.0926
580	5,124	166	1,000	1,166	-0.001259	-2.243	20.397	66,985	6.08	0.005232	0.05232	14,033	CONTINUE	4.83	20396.93	0.082233	217.0703
590	5,142	166	1,000	1,166	-0.001241	-2.255	20.374	66,911	6.07	0.005241	0.05241	13,980	CONTINUE	4.92	20374.38	0.082532	217.0479
600	5,160	166	1,000	1,166	-0.001224	-2.268	20.352	66,836	6.06	0.005250	0.05250	13,927	CONTINUE	5.00	20351.7	0.082834	217.0254
610	5,179	166	1,000	1,166	-0.001207	-2.280	20.329	66,762	6.05	0.005259	0.05259	13,873	CONTINUE	5.08	20328.91	0.083139	217.0027
620	5,198	166	1,000	1,166	-0.001191	-2.292	20.306	66,686	6.03	0.005268	0.05268	13,819	CONTINUE	5.17	20305.99	0.083447	216.9799
630	5,216	166	1,000	1,166	-0.001175	-2.303	20.283	66,611	6.02	0.005277	0.05277	13,766	CONTINUE	5.25	20282.95	0.083757	216.957
640	5,235	166	1,000	1,166	-0.001160	-2.315	20.260	66,535	6.01	0.005286	0.05286	13,712	CONTINUE	5.33	20259.8	0.084071	216.9339
650	5,254	166	1,000	1,166	-0.001145	-2.326	20.237	66,458	6.00	0.005295	0.05295	13,658	CONTINUE	5.42	20236.54	0.084387	216.9108
660	5,274	165	1,000	1,165	-0.001130	-2.338	20.213	66,381	5.99	0.005304	0.05304	13,604	CONTINUE	5.50	20213.16	0.084706	216.8875
670	5,293	165	1,000	1,165	-0.001116	-2.349	20.190	66,304	5.98	0.005314	0.05314	13,550	CONTINUE	5.58	20189.67	0.085027	216.8641
680	5,313	165	1,000	1,165	-0.001103	-2.360	20.166	66,227	5.97	0.005323	0.05323	13,496	CONTINUE	5.67	20166.07	0.085352	216.8406
690	5,333	165	1,000	1,165	-0.001090	-2.371	20.142	66,149	5.96	0.005332	0.05332	13,442	CONTINUE	5.75	20142.36	0.085679	216.817
700	5,353	165	1,000	1,165	-0.001077	-2.382	20.119	66,071	5.94	0.005342	0.05342	13,388	CONTINUE	5.83	20118.55	0.086009	216.7933
710	5,373	165	1,000	1,165	-0.001064	-2.392	20.095	65,992	5.93	0.005351	0.05351	13,334	CONTINUE	5.92	20094.63	0.086342	216.7695
720	5,393	165	1,000	1,165	-0.001052	-2.403	20.071	65,913	5.92	0.005361	0.05361	13,280	CONTINUE	6.00	20070.6	0.086678	216.7456
730	5,413	165	1,000	1,165	-0.001040	-2.413	20.046	65,834	5.91	0.005371	0.05371	13,226	CONTINUE	6.08	20046.47	0.087017	216.7216
740	5,434	165	1,000	1,165	-0.001029	-2.423	20.022	65,754	5.90	0.005381	0.05381	13,172	CONTINUE	6.17	20022.23	0.087358	216.6974
750	5,455	165	1,000	1,165	-0.001017	-2.434	19.998	65,675	5.89	0.005390	0.05390	13,118	CONTINUE	6.25	19997.89	0.087702	216.6732
760	5,476	165	1,000	1,165	-0.001025	-2.444	19.973	65,594	5.87	0.005400	0.05400	13,065	CONTINUE	6.33	19973.46	0.088046	216.6499
770	5,497	165	1,000	1,165	-0.001001	-2.454	19.949	65,514	5.86	0.005410	0.05410	13,012	CONTINUE	6.42	19948.92	0.088386	216.6499
780	5,518	165	1,000	1,165	-0.000998	-2.464	19.924	65,433	5.85	0.005419	0.05419	12,959	CONTINUE	6.50	19924.28	0.088729	216.6499
790	5,540	165	1,000	1,165	-0.000989	-2.474	19.900	65,352	5.84	0.005429	0.05429	12,907	CONTINUE	6.58	19899.54	0.089074	216.6499
800	5,561	165	1,000	1,165	-0.000979	-2.484	19.875	65,270	5.83	0.005439	0.05439	12,854	CONTINUE	6.67	19874.7	0.089422	216.6499
810	5,583	165	1,000	1,165	-0.000969	-2.493	19.850	65,188	5.82	0.005449	0.05449	12,801	CONTINUE	6.75	19849.77	0.089773	216.6499
820	5,605	165	1,000	1,165	-0.000960	-2.503	19.825	65,106	5.81	0.005459	0.05459	12,749	CONTINUE	6.83	19824.74	0.090127	216.6499
830	5,627	165	1,000	1,165	-0.000951	-2.512	19.800	65,023	5.80	0.005469	0.05469	12,696	CONTINUE	6.92	19799.62	0.090483	216.6499
840	5,649	165	1,000	1,165	-0.000942	-2.522	19.774	64,941	5.78	0.005479	0.05479	12,643	CONTINUE	7.00	19774.4	0.090842	216.6499
850	5,672	164	1,000	1,164	-0.000933	-2.531	19.749	64,857	5.77	0.005489	0.05489	12,591	CONTINUE	7.08	19749.09	0.091204	216.6499
860	5,695	164	1,000	1,164	-0.000925	-2.540	19.724	64,774	5.76	0.005499	0.05499	12,538	CONTINUE	7.17	19723.69	0.091569	216.6499
870	5,718	164	1,000	1,164	-0.000916	-2.550	19.698	64,690	5.75	0.005510	0.05510	12,486	CONTINUE	7.25	19698.19	0.091937	216.6499
880	5,741	164	1,000	1,164	-0.000908	-2.559	19.673	64,606	5.74	0.005520	0.05520	12,433	CONTINUE	7.33	19672.6	0.092307	216.6499
890	5,764	164	1,000	1,164	-0.000900	-2.568	19.647	64,522	5.73	0.005530	0.05530	12,381	CONTINUE	7.42	19646.93	0.09268	216.6499
900	5,787	164	1,000	1,164	-0.000892	-2.577	19.621	64,437	5.71	0.005541	0.05541	12,328	CONTINUE	7.50	19621.16	0.093056	216.6499
910	5,811	164	1,000	1,164	-0.000884	-2.585	19.595	64,352	5.70	0.005551	0.05551	12,276	CONTINUE	7.58	19595.31	0.093435	216.6499
920	5,834	164	1,000	1,164	-0.000877	-2.594	19.569	64,267	5.69	0.005562	0.05562	12,224	CONTINUE	7.67	19569.37	0.093817	216.6499
930	5,858	164	1,000	1,164	-0.000869	-2.603	19.543	64,182	5.68	0.005572	0.05572	12,171	CONTINUE	7.75	19543.34	0.094201	216.6499
940	5,882	164	1,000	1,164	-0.000862	-2.611	19.517	64,096	5.67	0.005583	0.05583	12,119	CONTINUE	7.83	19517.22	0.094589	216.6499
950	5,907	164	1,000	1,164	-0.000855	-2.620	19.491	64,010	5.66	0.005594	0.05594	12,067	CONTINUE	7.92	19491.02	0.094979	216.6499
960	5,931	164	1,000	1,164	-0.000848	-2.628	19.465	63,924	5.64	0.005604	0.05604	12,015	CONTINUE	8.00	19464.74	0.095372	216.6499
970	5,956	164	1,000	1,164	-0.000841	-2.637	19.438	63,837	5.63	0.005615	0.05615	11,963	CONTINUE	8.08	19438.37	0.095768	216.6499
980	5,981	164	1,000	1,164	-0.000834	-2.645	19.412	63,750	5.62	0.005626	0.05626	11,911	CONTINUE	8.17	19411.92	0.096168	216.6499
990	6,006	164	1,000	1,164	-0.000827	-2.653	19.385	63,663	5.61	0.005637	0.05637	11,859	CONTINUE	8.25	19385.38	0.09657	216.6499
1000	6,031	164	1,000	1,164	-0.000821	-2.662	19.359	63,576	5.60	0.005648	0.05648	11,807	CONTINUE	8.33	19358.77	0.096974	216.6499
1010	6,056	164	1,000	1,164	-0.000814	-2.670	19.332	63,488	5.59	0.005659	0.05659	11,755	CONTINUE	8.42	19332.07	0.097382	216.6499
1020	6,082	164	1,000	1,164	-0.000808	-2.678	19.305	63,400	5.57	0.005670	0.05670	11,703	CONTINUE	8.50	19305.29	0.097793	216.6499
1030	6,107	163	1,000	1,163	-0.000801	-2.686	19.278	63,312	5.56	0.005681	0.05681	11,651	CONTINUE	8.58	19278.43	0.098207	216.6499
1040	6,133	163	1,000	1,163	-0.000795	-2.694	19.251	63,223	5.55	0.005693	0.05693	11,600	CONTINUE	8.67	19251.49	0.098624	216.6499
1050	6,160	163	1,000	1,163	-0.000789	-2.702	19.224	63,135	5.54	0.005704	0.05704	11,548	CONTINUE	8.75	19224.47	0.099044	216.6499
1060	6,186	163	1,000	1,163	-0.000783	-2.710	19.197	63,046	5.53	0.005715	0.05715	11,497	CONTINUE	8.83	19197.38	0.099467	216.6499
1070	6,212	163	1,000	1,163	-0.000777	-2.717	19.170	62,956	5.52	0.005727	0.05727	11,445	CONTINUE	8.92	19170.2	0.099893	216.6499
1080	6,239	163	1,000	1,163	-0.000772	-2.725	19.143	62,867	5.50	0.005738	0.05738	11,394	CONTINUE	9.00	19142.95	0.100321	216.6499
1090	6,266	163	1,000	1,163	-0.000766	-2.733	19.116	62,777	5.49	0.005750	0.05750	11,343	CONTINUE	9.08	19115.63	0.100754	216.6499
1100	6,293	163	1,000	1,163	-0.000760	-2.740	19.088	62,687	5.48	0.005761	0.05761	11,291	CONTINUE	9.17	19088.22	0.101189	216.6499
1110	6,320	163	1,000	1,163	-0.000755	-2.748	19.061	62,597	5.47	0.005773	0.05773	11,240	CONTINUE	9.25	19060.74	0.101627	216.6499
1120	6,348	163	1,000	1,163	-0.000749	-2.755	19.033	62,506	5.46	0.005785	0.05785	11,189	CONTINUE	9.33	19033.19	0.102068	216.6499
1130	6,375	163	1,000	1,163	-0.000744	-2.763	19.006	62,416	5.44	0.005797	0.05797	11,138	CONTINUE	9.42	19005.56	0.102513	216.6499
1140	6,403	163	1,000	1,163	-0.000738	-2.770	18.978	62,325	5.43	0.005808	0.05808	11,088	CONTINUE	9.50	18977.86	0.10296	216.6499
1150	6,431	163	1,000	1,163	-0.000733	-2.778	18.950	62,233	5.42	0.005820	0.05820	11,037	CONTINUE	9.58	18950.08	0.103411	216.6499
1160	6,459	163	1,000	1,163	-0.000728	-2.785	18.922	62,142	5.41	0.005832	0.05832	10,986	CONTINUE	9.67	18922.23	0.103865	216.6499
1170	6,488	163	1,000	1,163	-0.000723	-2.792	18.894	62,050	5.40	0.005844	0.05844	10,936	CONTINUE	9.75	18894.31	0.104322	216.6499
1180	6,516	163	1,000	1,163	-0.000717	-2.799	18.866	61,958	5.39	0.005856	0.05856	10,885	CONTINUE	9.83	18866.32	0.104782	216.6499
1190	6,545	163	1,000	1,163	-0.000712	-2.806	18.838	61,866	5.37	0.005868	0.05868	10,835	CONTINUE	9.92	18838.26	0.105246	216.6499
1200	6,574	162	1,000	1,162	-0.000707	-2.813	18.810	61,774	5.36	0.005881	0.05881	10,785	CONTINUE	10.00	18810.12	0.105713	216.6499
1210	6,604	162	1,000	1,162	-0.000702	-2.820	18.782	61,681	5.35	0.005893	0.05893	10,734	CONTINUE	10.08	18781.92	0.106183	216.6499
1220	6,633	162	1,000	1,162	-0.000697	-2.827	18.754	61,588	5.34	0.005905	0.05905	10,684	CONTINUE	10.17	18753.65	0.106656	216.6499
1230	6,663	162	1,000	1,162	-0.000693	-2.834	18.725	61,495	5.33	0.005918	0.05918	10,634	CONTINUE	10.25	18725.3	0.107133	216.6499
1240	6,692	162	1,000	1,162	-0.000688	-2.841	18.697	61,402	5.31	0.005930	0.05930	10,585	CONTINUE	10.33	18696.89	0.107613	216.6499
1250	6,722	162	1,000	1,162	-0.000683	-2.848	18.668	61,308	5.30	0.005942	0.05942	10,535	CONTINUE	10.42	18668.41	0.108096	216.6499
1260	6,753	162	1,000	1,162	-0.000678	-2.855	18.640	61,215	5.29	0.005955	0.05955	10,485	CONTINUE	10.50	18639.86	0.108582	216.6499
1270	6,783	162	1,000	1,162	-0.000674	-2.862	18.611	61,121	5.28	0.005968	0.05968	10,436	CONTINUE	10.58	18611.25	0.109072	216.6499
1280	6,814	162	1,000	1,162	-0.000669	-2.868	18.583	61,026	5.27	0.005980	0.05980	10,386	CONTINUE	10.67	18582.56	0.109566	216.6499
1290	6,845	162	1,000	1,162	-0.000664	-2.875	18.554	60,932	5.25	0.005993	0.05993	10,337	CONTINUE	10.75	18553.81	0.110062	216.6499
1300	6,876	162	1,000	1,162	-0.000660	-2.881	18.525	60,837	5.24	0.006006	0.06006	10,288	CONTINUE	10.83	18525	0.110562	216.6499
1310	6,907	162	1,000	1,162	-0.000655	-2.888	18.496	60,743	5.23	0.006019	0.06019	10,239	CONTINUE	10.92	18496.12	0.111066	216.6499
1320	6,939	162	1,000	1,162	-0.000651	-2.895	18.467	60,648	5.22	0.006032	0.06032	10,190	CONTINUE	11.00	18467.17	0.111573	216.6499
1330	6,970	162	1,000	1,162	-0.000646	-2.901	18.438	60,552	5.21	0.006045	0.06045	10,141	CONTINUE	11.08	18438.16	0.112083	216.6499
1340	7,002	162	1,000	1,162	-0.000642	-2.907	18.409	60,457	5.20	0.006058	0.06058	10,092	CONTINUE	11.17	18409.09	0.112597	216.6499
1350	7,035	162	1,000	1,162	-0.000638	-2.914	18.380	60,361	5.18	0.006071	0.06071	10,044	CONTINUE	11.25	18379.95	0.113115	216.6499
1360	7,067	162	1,000	1,162	-0.000633	-2.920	18.351	60,265	5.17	0.006084	0.06084	9,995	CONTINUE	11.33	18350.75	0.113636	216.6499
1370	7,100	161	1,000	1,161	-0.000629	-2.926	18.321	60,169	5.16	0.006097	0.06097	9,947	CONTINUE	11.42	18321.48	0.11416	216.6499
1380	7,132	161	1,000	1,161	-0.000625	-2.933	18.292	60,073	5.15	0.006110	0.06110	9,899	CONTINUE	11.50	18292.16	0.114688	216.6499
1390	7,166	161	1,000	1,161	-0.000620	-2.939	18.263	59,976	5.14	0.006124	0.06124	9,850	CONTINUE	11.58	18262.77	0.11522	216.6499
1400	7,199	161	1,000	1,161	-0.000616	-2.945	18.233	59,880	5.12	0.006137	0.06137	9,802	END	11.67	18233.32	0.115755	216.6499

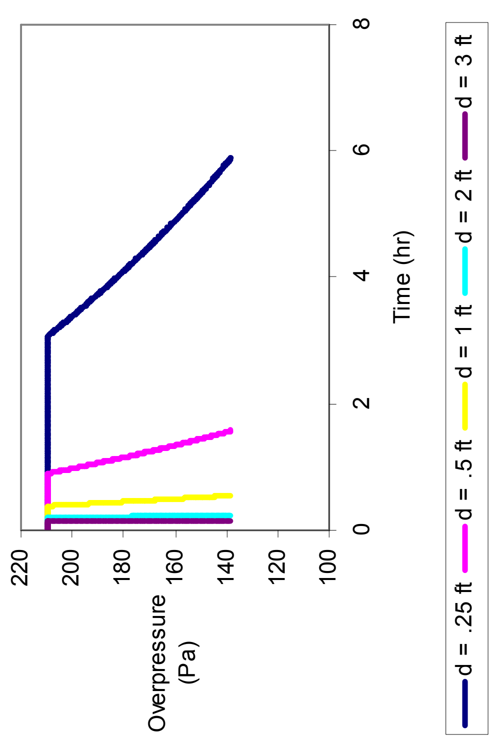
Isothermal Data (continued)

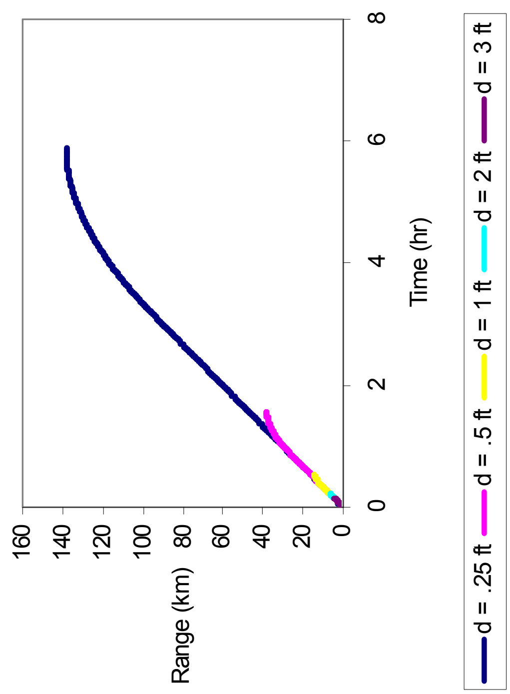
time inc =	10	sec	mw He =	0.004	kg/mole	R =	8.314	m^3 Pa / mole K	rho 0 =	1.225	kg/m^3	xs area =	1648.36	m^2			
H =	6.82	km	mw air =	0.029	kg/mole	T 0 =	288.15	K	rho0 He =	0.179	kg/m^3	drag coeff =	0.3				
p0 =	101325	Pa	gravity =	9.81	m/sec^2	init alt =	59976	18.262692 km	dp/dt factor	0.5		A =	81.2	m			
mass st =	1000	kg	p op	210	Pa	area hole =	0.0728	m^2	dV/dt factor	0.5		B =	20.3	m			

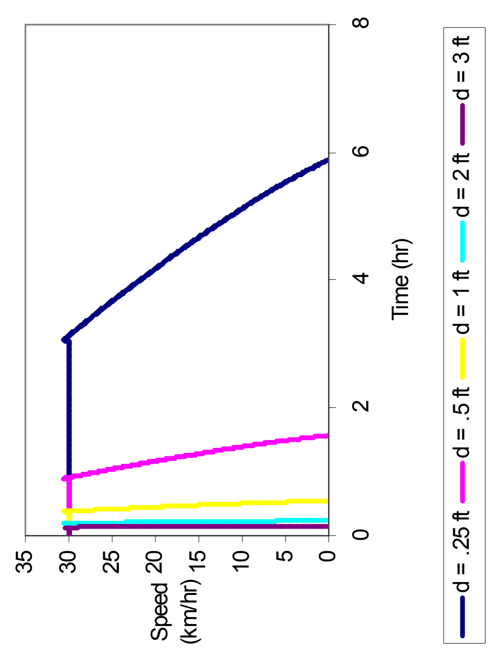
time sec	P atm Pa	P env	delta P	P op	mass He kg	mass tot kg	vel He m/sec	mass flow kg/sec	delta m kg	rho He kg/m^3	delta vol	vol m^3	a y m/sec^2	v y m/sec	alt km	alt ft	alt m	temp K	rho Air kg/m^3	vel x-range km/hr	dist x-range km
1390	7,198.894	7,408.894	0.00	210.0000	165.4396	1,165.440	5.12	0	0	0.016453		10,055.29	0	0	18.263	59,976	18262.69	216.6499	0.115757	30.752	11.580
1400	7,198.894	7,407.520	1.37420	208.6258	165.3782	1,165.378	5.11	0.006137132	0.0613713	0.016450	1.865051	10,053.42	-0.0013034	-0.0130337	18.263	59,976	18262.56	216.6499	0.115759	30.340	11.664
1410	7,199.042	7,406.298	1.36969	207.2561	165.3170	1,165.317	5.09	0.006115884	0.0611588	0.016447	1.858938	10,051.56	-0.0025929	-0.0389626	18.262	59,974	18262.17	216.6499	0.115766	29.926	11.747
1420	7,199.484	7,405.375	1.36518	205.8909	165.2561	1,165.256	5.07	0.006094585	0.0609459	0.016444	1.852807	10,049.71	-0.0038383	-0.0773460	18.261	59,972	18261.4	216.6499	0.11578	29.510	11.829
1430	7,200.362	7,404.893	1.36063	204.5303	165.1953	1,165.195	5.06	0.006073173	0.0607317	0.016441	1.846638	10,047.86	-0.0049870	-0.1272155	18.260	59,968	18260.13	216.6499	0.115803	29.092	11.910
1440	7,201.807	7,404.981	1.35605	203.1743	165.1348	1,165.135	5.04	0.006051591	0.0605159	0.016438	1.840414	10,046.02	-0.0059697	-0.1869123	18.258	59,961	18258.26	216.6499	0.115838	28.672	11.990
1450	7,203.930	7,405.753	1.35141	201.8228	165.0745	1,165.075	5.02	0.006029787	0.0602979	0.016435	1.834119	10,044.19	-0.0067134	-0.2540463	18.256	59,953	18255.72	216.6499	0.115884	28.249	12.068
1460	7,206.817	7,407.293	1.34671	200.4761	165.0145	1,165.014	5.00	0.006007717	0.0600772	0.016432	1.827739	10,042.36	-0.0071585	-0.3256317	18.252	59,942	18252.46	216.6499	0.115943	27.824	12.146
1470	7,210.518	7,409.652	1.34194	199.1342	164.9546	1,164.955	4.99	0.005985351	0.0598535	0.016429	1.821266	10,040.54	-0.0072775	-0.3984066	18.248	59,929	18248.48	216.6499	0.116016	27.397	12.222
1480	7,215.050	7,412.847	1.33710	197.7971	164.8950	1,164.895	4.97	0.005962672	0.0596267	0.016426	1.814695	10,038.73	-0.0070867	-0.4692732	18.244	59,914	18243.78	216.6499	0.116102	26.968	12.297
1490	7,220.391	7,416.856	1.33218	196.4649	164.8356	1,164.836	4.95	0.005939679	0.0593968	0.016423	1.808024	10,036.92	-0.0066455	-0.5357283	18.238	59,896	18238.43	216.6499	0.1162	26.536	12.370
1500	7,226.493	7,421.631	1.32720	195.1377	164.7764	1,164.776	4.93	0.005916387	0.0591639	0.016420	1.801258	10,035.12	-0.0060417	-0.5961454	18.232	59,877	18232.46	216.6499	0.11631	26.102	12.443
1510	7,233.290	7,427.106	1.32215	193.8156	164.7175	1,164.717	4.91	0.005892822	0.0589282	0.016417	1.794406	10,033.32	-0.0053689	-0.6498340	18.226	59,855	18225.97	216.6499	0.116429	25.665	12.514
1520	7,240.706	7,433.205	1.31704	192.4985	164.6588	1,164.659	4.89	0.005869015	0.0586901	0.016414	1.787476	10,031.53	-0.0047059	-0.6968929	18.219	59,833	18219	216.6499	0.116557	25.226	12.584
1530	7,248.668	7,439.854	1.31189	191.1867	164.6003	1,164.600	4.87	0.005845002	0.0584500	0.016411	1.780480	10,029.75	-0.0041059	-0.7379521	18.212	59,808	18211.62	216.6499	0.116693	24.785	12.653
1540	7,257.108	7,446.988	1.30669	189.8800	164.5421	1,164.542	4.85	0.005820818	0.0582082	0.016408	1.773428	10,027.98	-0.0035951	-0.7739033	18.204	59,783	18203.88	216.6499	0.116835	24.340	12.721
1550	7,265.970	7,454.549	1.30146	188.5785	164.4842	1,164.484	4.83	0.005796493	0.0579649	0.016405	1.766329	10,026.21	-0.0031785	-0.8056880	18.196	59,756	18195.82	216.6499	0.116984	23.893	12.787
1560	7,275.207	7,462.490	1.29620	187.2823	164.4265	1,164.426	4.81	0.005772053	0.0577205	0.016403	1.759192	10,024.46	-0.0028479	-0.8341666	18.187	59,729	18187.48	216.6499	0.117138	23.444	12.852
1570	7,284.784	7,470.775	1.29092	185.9914	164.3690	1,164.369	4.79	0.00574752	0.0574752	0.016400	1.752022	10,022.70	-0.0025892	-0.8600585	18.179	59,701	18178.88	216.6499	0.117297	22.991	12.916
1580	7,294.671	7,479.376	1.28561	184.7058	164.3117	1,164.312	4.77	0.00572291	0.0572291	0.016397	1.744825	10,020.96	-0.0023872	-0.8839302	18.170	59,672	18170.04	216.6499	0.11746	22.535	12.979
1590	7,304.846	7,488.271	1.28029	183.4255	164.2548	1,164.255	4.75	0.005698239	0.0569824	0.016394	1.737606	10,019.22	-0.0022280	-0.9062107	18.161	59,642	18160.98	216.6499	0.117628	22.077	13.040
1600	7,315.292	7,497.443	1.27496	182.1505	164.1980	1,164.198	4.73	0.005673515	0.0567352	0.016391	1.730367	10,017.49	-0.0021005	-0.9272160	18.152	59,612	18151.71	216.6499	0.1178	21.615	13.100
1610	7,325.996	7,506.877	1.26961	180.8809	164.1415	1,164.142	4.71	0.005648749	0.0564875	0.016388	1.723111	10,015.77	-0.0019961	-0.9471766	18.142	59,580	18142.23	216.6499	0.117976	21.150	13.159
1620	7,336.947	7,516.563	1.26426	179.6167	164.0853	1,164.085	4.69	0.005623946	0.0562395	0.016386	1.715840	10,014.05	-0.0019083	-0.9662599	18.133	59,549	18132.57	216.6499	0.118156	20.682	13.216
1630	7,348.135	7,526.492	1.25889	178.3578	164.0293	1,164.029	4.67	0.005599115	0.0559911	0.016383	1.708557	10,012.34	-0.0018329	-0.9845886	18.123	59,516	18122.73	216.6499	0.11834	20.211	13.272
1640	7,359.553	7,536.657	1.25352	177.1042	163.9736	1,163.974	4.65	0.005574258	0.0557426	0.016380	1.701263	10,010.64	-0.0017666	-1.0022545	18.113	59,483	18112.7	216.6499	0.118527	19.736	13.327
1650	7,371.193	7,547.050	1.24813	175.8561	163.9181	1,163.918	4.63	0.005549382	0.0554938	0.016377	1.693958	10,008.95	-0.0017073	-1.0193276	18.103	59,450	18102.51	216.6499	0.118718	19.257	13.381
1660	7,383.052	7,557.665	1.24275	174.6134	163.8628	1,163.863	4.61	0.005524489	0.0552449	0.016374	1.686645	10,007.26	-0.0016536	-1.0358633	18.092	59,416	18092.15	216.6499	0.118912	18.774	13.433
1670	7,395.122	7,568.498	1.23735	173.3760	163.8078	1,163.808	4.59	0.005499585	0.0549958	0.016372	1.679325	10,005.58	-0.0016043	-1.0519062	18.082	59,381	18081.63	216.6499	0.119109	18.288	13.484
1680	7,407.399	7,579.543	1.23195	172.1441	163.7531	1,163.753	4.57	0.005474671	0.0547467	0.016369	1.671998	10,003.91	-0.0015588	-1.0674937	18.071	59,346	18070.96	216.6499	0.11931	17.797	13.533
1690	7,419.879	7,590.796	1.22655	170.9175	163.6986	1,163.699	4.55	0.005449752	0.0544975	0.016366	1.664666	10,002.25	-0.0015164	-1.0826576	18.060	59,311	18060.13	216.6499	0.119514	17.302	13.581
1700	7,432.557	7,602.254	1.22114	169.6964	163.6443	1,163.644	4.53	0.005424831	0.0542483	0.016363	1.657329	10,000.59	-0.0014768	-1.0974252	18.049	59,275	18049.16	216.6499	0.119721	16.803	13.628
1710	7,445.431	7,613.912	1.21574	168.4806	163.5903	1,163.590	4.51	0.005399909	0.0539991	0.016361	1.649989	9,998.94	-0.0014396	-1.1118209	18.038	59,238	18038.04	216.6499	0.119931	16.299	13.673
1720	7,458.496	7,625.767	1.21033	167.2703	163.5366	1,163.537	4.49	0.005374991	0.0537499	0.016358	1.642646	9,997.30	-0.0014045	-1.1258662	18.027	59,201	18026.78	216.6499	0.120144	15.790	13.717
1730	7,471.750	7,637.815	1.20491	166.0654	163.4831	1,163.483	4.47	0.005350078	0.0535008	0.016355	1.635301	9,995.66	-0.0013714	-1.1395805	18.015	59,164	18015.38	216.6499	0.12036	15.276	13.759
1740	7,485.189	7,650.055	1.19950	164.8659	163.4298	1,163.430	4.45	0.005325172	0.0532517	0.016353	1.627955	9,994.03	-0.0013401	-1.1529812	18.004	59,126	18003.85	216.6499	0.120579	14.757	13.800
1750	7,498.811	7,662.483	1.19409	163.6718	163.3768	1,163.377	4.43	0.005300276	0.0530028	0.016350	1.620608	9,992.41	-0.0013103	-1.1660843	17.992	59,088	17992.19	216.6499	0.120801	14.233	13.840
1760	7,512.613	7,675.096	1.18867	162.4831	163.3241	1,163.324	4.41	0.005275393	0.0527539	0.016347	1.613261	9,990.80	-0.0012820	-1.1789043	17.980	59,049	17980.4	216.6499	0.121026	13.702	13.878
1770	7,526.592	7,687.892	1.18326	161.2999	163.2716	1,163.272	4.39	0.005250523	0.0525052	0.016345	1.605915	9,989.19	-0.0012550	-1.1914544	17.968	59,010	17968.49	216.6499	0.121253	13.166	13.914
1780	7,540.747	7,700.869	1.17785	160.1220	163.2193	1,163.219	4.37	0.005225669	0.0522567	0.016342	1.598570	9,987.59	-0.0012293	-1.2037470	17.956	58,970	17956.45	216.6499	0.121484	12.624	13.950
1790	7,555.075	7,714.024	1.17244	158.9496	163.1673	1,163.167	4.35	0.005200833	0.0520083	0.016340	1.591227	9,986.00	-0.0012046	-1.2157932	17.944	58,930	17944.29	216.6499	0.121717	12.075	13.983
1800	7,569.573	7,727.356	1.16703	157.7825	163.1156	1,163.116	4.33	0.005176017	0.0517602	0.016337	1.583887	9,984.42	-0.0011810	-1.2276037	17.932	58,890	17932.02	216.6499	0.121953	11.518	14.015
1810	7,584.241	7,740.862	1.16163	156.6209	163.0640	1,163.064	4.31	0.005151222	0.0515122	0.016334	1.576550	9,982.84	-0.0011584	-1.2391879	17.920	58,849	17919.63	216.6499	0.122191	10.955	14.046
1820	7,599.076	7,754.541	1.15622	155.4647	163.0128	1,163.013	4.29	0.00512645	0.0512645	0.016332	1.569216	9,981.27	-0.0011367	-1.2505550	17.907	58,808	17907.12	216.6499	0.122433	10.384	14.074
1830	7,614.077	7,768.391	1.15082	154.3139	162.9618	1,162.962	4.27	0.005101702	0.0510170	0.016329	1.561886	9,979.71	-0.0011158	-1.2617134	17.895	58,767	17894.5	216.6499	0.122676	9.804	14.102
1840	7,629.241	7,782.410	1.14542	153.1685	162.9110	1,162.911	4.25	0.00507698	0.0507698	0.016327	1.554561	9,978.16	-0.0010957	-1.2726708	17.882	58,725	17881.78	216.6499	0.122923	9.216	14.127
1850	7,644.568	7,796.596	1.14003	152.0284	162.8605	1,162.860	4.23	0.005052286	0.0505229	0.016324	1.547241	9,976.61	-0.0010764	-1.2834346	17.869	58,683	17868.94	216.6499	0.123172	8.619	14.151
1860	7,660.055	7,810.949	1.13464	150.8938	162.8102	1,162.810	4.21	0.005027621	0.0502762	0.016322	1.539926	9,975.07	-0.0010577	-1.2940115	17.856	58,640	17856	216.6499	0.123423	8.012	14.173
1870	7,675.702	7,825.467	1.12925	149.7645	162.7602	1,162.760	4.19	0.005002986	0.0500299	0.016319	1.532617	9,973.54	-0.0010397	-1.3044082	17.843	58,598	17842.96	216.6499	0.123678	7.394	14.194
1880	7,691.507	7,840.148	1.12387	148.6407	162.7104	1,162.710	4.17	0.004978382	0.0497838	0.016317	1.525314	9,972.01	-0.0010222	-1.3146305	17.830	58,554	17829.81	216.6499	0.123934	6.765	14.213
1890	7,707.469	7,854.991	1.11850	147.5222	162.6608	1,162.661	4.15	0.004953811	0.0495381	0.016314	1.518018	9,970.49	-0.0010054	-1.3246841	17.817	58,511	17816.57	216.6499	0.124193	6.125	14.230
1900	7,723.586	7,869.995	1.11313	146.4090	162.6115	1,162.612	4.13	0.004929274	0.0492927	0.016312	1.510729	9,968.98	-0.0009890	-1.3345745	17.803	58,467	17803.22	216.6499	0.124455	5.471	14.245
1910	7,739.858	7,885.159	1.10776	145.3013	162.5625	1,162.562	4.11	0.004904772	0.0490477	0.016309	1.503448	9,967.48	-0.0009732	-1.3443066	17.790	58,423	17789.78	216.6499	0.124719	4.803	14.258
1920	7,756.283	7,900.482	1.10240	144.1989	162.5137	1,162.514	4.09	0.004880307	0.0488031	0.016307	1.496174	9,965.98	-0.0009579	-1.3538852	17.776	58,378	17776.24	216.6499	0.124986	4.120	14.270
1930	7,772.860	7,915.962	1.09705	143.1018	162.4651	1,162.465	4.07	0.004855878	0.0485588	0.016304	1.488908	9,964.49	-0.0009430	-1.3633149	17.763	58,334	17762.6	216.6499	0.125255	3.421	14.279
1940	7,789.589	7,931.599	1.09170	142.0101	162.4168	1,162.417	4.05	0.004831488	0.0483149	0.016302	1.481651	9,963.01	-0.0009285	-1.3725998	17.749	58,289	17748.88	216.6499	0.125526	2.704	14.287
1950	7,806.468	7,947.391	1.08636	140.9238	162.3688	1,162.369	4.03	0.004807138	0.0480714	0.016300	1.474403	9,961.54	-0.0009144	-1.3817440	17.735	58,243	17735.06	216.6499	0.1258	1.967	14.292
1960	7,823.496	7,963.339	1.08103	139.8427	162.3209	1,162.321	4.01	0.004782828	0.0478283	0.016297	1.467164	9,960.07	-0.0009007	-1.3907513	17.721	58,198	17721.15	216.6499	0.126076	1.208	14.296
1970	7,840.673	7,979.440	1.07570	138.7670	162.2733	1,162.273	3.99	0.004758559	0.0475856	0.016295	1.459935	9,958.61	-0.0008874	-1.3996254	17.707	58,152	17707.16	216.6499	0.126355	0.425	14.297

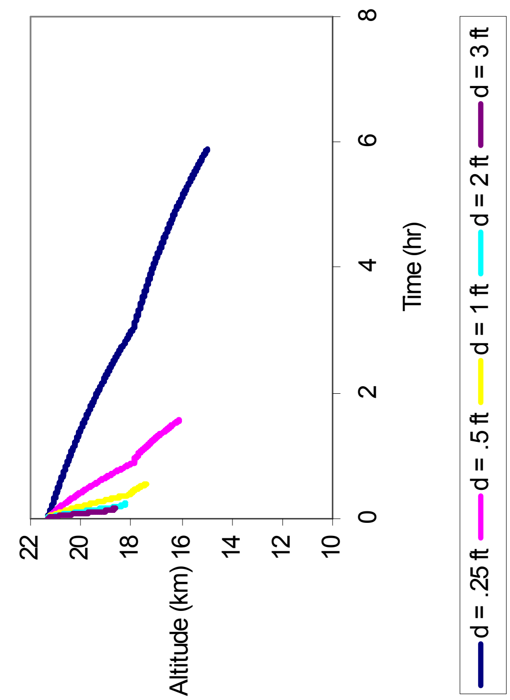
Appendix C – Modeling Performance Data

Case 1 – Maintain Constant Overpressure

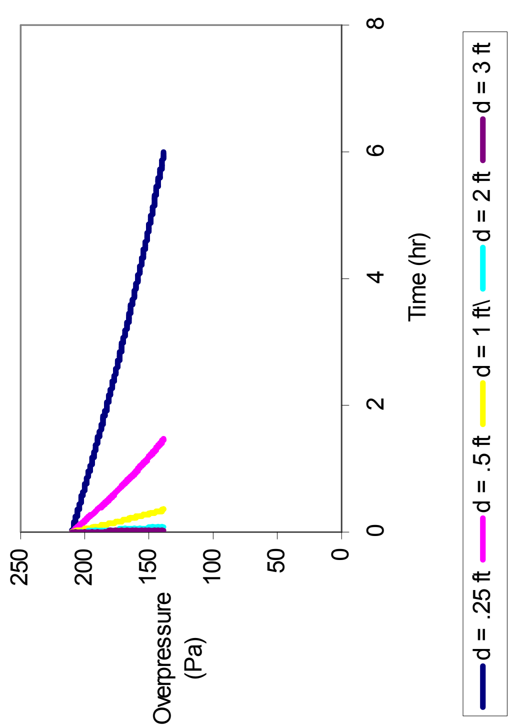


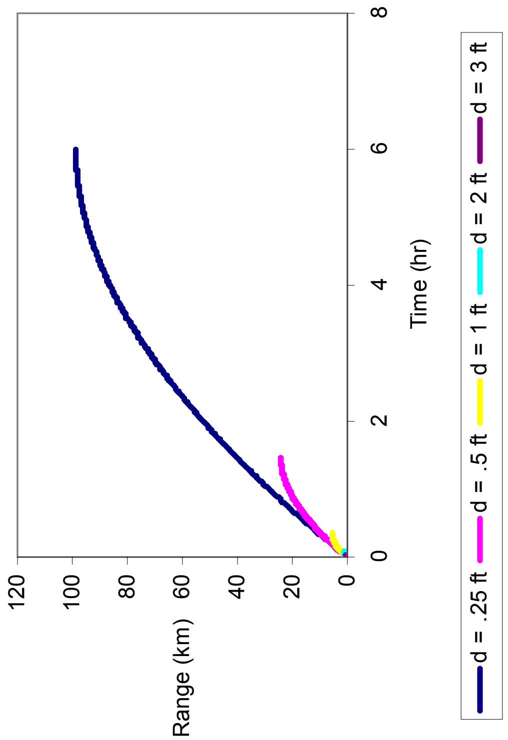


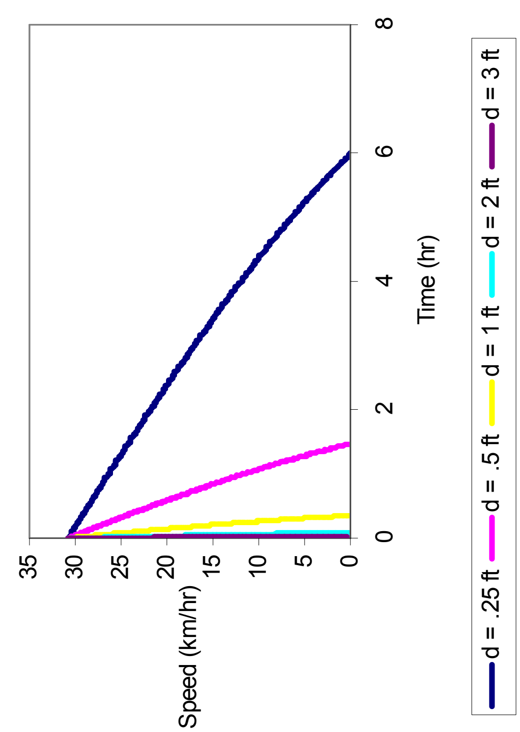


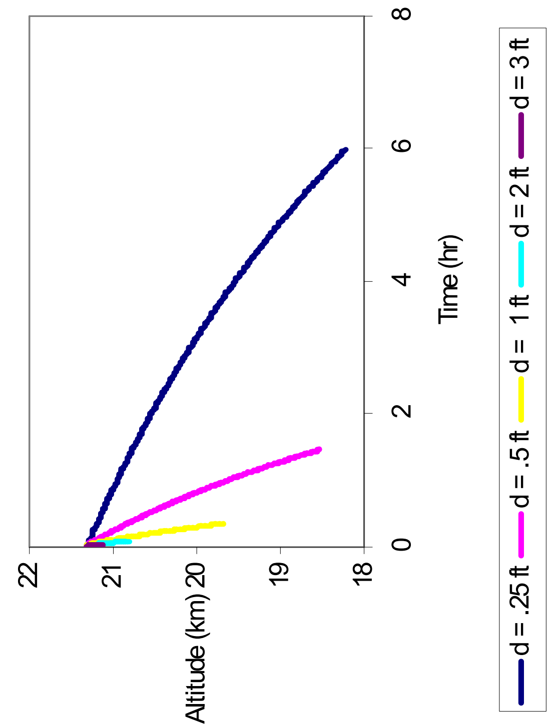


Case 2 – Slow Depressurization









Appendix D – Army High-Altitude Airship Publication

UNITED STATES ARMY
SPACE AND MISSILE
DEFENSE COMMAND

Future Warfare Center

High Altitude Airship

Summary

- Station-keeping Endurance—1 month
- Station-keeping Altitude—65,000 ft mean-sea-level (MSL)
- Payload Weight—500 lb
- Payload Power—3 kW
- Cruise Speed—25 kts
- Station-keeping Accuracy— < 2 km 50 percent of time, <150 km 95 percent of time
- Command and Control—Remotely Piloted

HAA is an Advanced Concept Technology Demonstration (ACTD), with Office of the Secretary of Defense oversight, North American Aerospace Defense Command user sponsor, U.S. Army lead service, Missile Defense Agency executing agent/technical manager, Space and Missile Defense Technical Center transitional manager, and Space and Missile Defense Future Warfare Center operational manager.

The objective of this ACTD is to demonstrate the engineering feasibility and potential military utility of an unmanned, untethered, gas-filled, solar powered airship that can fly at 65,000 feet. The prototype airship developed under this effort will be capable of continuous flight for up to a month while carrying a multi-mission payload. This ACTD is intended as a developmental step toward an objective HAA that can self-deploy from the continental United States (CONUS) to worldwide locations and remain on station in a geo-stationary position for a year or more before returning to a fixed launch and recovery area in CONUS for service on the ground.

Secure the High Ground

High Altitude Airship

Future Warfare Center

Program Objectives

- Design and produce a lighter-than-air, High Altitude Airship — Advanced Concept Technology Demonstration (ACTD) Prototype
- Demonstrate the feasibility and potential military utility of an unmanned, untethered, airship that can fly at nominal 65,000 feet mean-sea-level altitude for up to one month while carrying a multi-mission payload

Benefits

- Persistent 24/7 capability
- Low cost, rapid reconstitution of capabilities
- Multi-mission, exchangeable/repairable/upgradeable payloads
- Long duration aloft greater than an unmanned aerial vehicle
- Low inherent detectability, observability
- Repositionable
- Improves performance of nearly all sensors

Altitude

The desired altitude to operate an HAA is approximately 65,000 feet. This is due to many factors, including it is above the weather and Federal Aviation Administration air traffic control. The winds are relatively benign and the thin atmosphere allows for extended range of Electro-Optical/Infra-Red (EO/IR) equipment. Importantly, at 65,000 feet, the HAA will have more than a 600-mile footprint on the ground

Experimentation Architecture

The HAA fits into a layered architecture. It operates at the same altitude as the U2 and Global Hawk. While not providing the same ability for quick reaction operations, once on station, it provides long endurance continuous/persistent support that is not practical using combinations of manned and unmanned aircraft. Because it maintains geo-stationary position at 12 miles above the Earth, it does not have the latency issues associated with geo-synchronous satellites. The airship serves a transformational purpose by filling the capability gap between aerial vehicles and satellites.

For more information, please contact:
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Vita

Major Charles W. Vogt, Jr., graduated from the University of Arizona in Tucson, Arizona with a Bachelor of Science degree in Mechanical Engineering in Dec 1990. He was commissioned through the Detachment 20 AFROTC at the University of Arizona.

His first assignment was at Norton AFB, California as a developmental engineer in September 1991. He cross-flowed into space and missile operations in February 1994, and held crew commander, instructor, and flight commander positions at the 341st Space Wing, Malmstrom AFB, Montana and the 45th Space Wing, Cape Canaveral AFS, Florida. During this time he completed a Master's of Science Degree in Engineering Management from the Florida Institute of Technology in Melbourne, Florida. Prior to arriving at the Air Force Institute of Technology (AFIT), Major Vogt served as Deputy Division Chief, Contingencies Analyses Division, Air Force Studies and Analyses Agency in the Pentagon. In September 2004, he entered the AFIT Graduate School of Engineering and Management as an intermediate developmental education (IDE) student. Upon graduation, he will be assigned to Headquarters Air Force Space Command A-3RS, Peterson Air Force Base, Colorado.

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14. ABSTRACT
This study investigates the ability of a high-altitude airship to maintain lift following the compromise of its lifting gas envelope. Accepted engineering principles are applied to develop a model that provides comparative analyses for airship depressurization alternatives following hull compromise. Specifically, maintaining lifting gas envelope overpressure to provide controllability in wind currents while sacrificing some buoyancy is compared with allowing envelope depressurization to occur with the goal of maintaining greater buoyancy as long as possible. The model provides insights to alternatives for recovering a damaged vehicle and its payload. In particular, the analysis demonstrates that maintaining the ability to navigate while forfeiting buoyancy can provide additional down-range maneuver capability. In some cases preserving the airship's hull overpressure for some period of time following compromise, vice allowing a slow depressurization to atmospheric equilibrium, extends the distance a damaged airship can sustain controlled navigation as much as eighty percent. However, the airship will forfeit nearly twenty percent of the altitude it would otherwise preserve by not forcing a constant hull overpressure.

15. SUBJECT TERMS
Airship, High Altitude, Near Space, Survivability, Lighter-than-Air

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